ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

PERFORMANCE OF A GEOTHERMAL RESERVOIR UNDER UNITIZED AND COMPETITIVE UTILIZATION CONDITIONS

M.Sc. THESIS

SULEMAN SALIA

Department of Petroleum and Natural Gas Engineering

Petroleum and Natural Gas Engineering Programme

October, 2015

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

PERFORMANCE OF A GEOTHERMAL RESERVOIR UNDER UNITIZED AND COMPETITIVE UTILIZATION CONDITIONS

M.Sc. THESIS

SULEMAN SALIA
(505121503)

Department of Petroleum and Natural Gas Engineering

Petroleum and Natural Gas Engineering Programme

Thesis Advisor: Asst. Prof. Dr. İ. Metin Mıhçakan

October, 2015

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BİR JEOTERMAL REZERVUARIN BİRİMLEŞTİRİLMİŞ VE REKABETÇİ YARARLANMA KOŞULLARI ALTINDAKİ PERFORMANSI

YÜKSEK LİSANS TEZİ

SULEMAN SALIA
(505121503)

Petrol ve Doğal Gaz Mühendisliği Anabilim Dalı

Petrol ve Doğal Gaz Mühendisliği Programı

Tez Danışmanı: Asst. Prof. Dr. İ. Metin Mıhçakan

Ekim, 2015

Suleman Salia, a **M.Sc.** student of ITU **Institute of Energy** student ID 505121503, successfully defended the **thesis** entitled “Performance of a Geothermal Reservoir under Unitized and Competitive Utilization ”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Asst. Prof. Dr. İ. Metin Mıhçakan** İstanbul Technical University	....
Jury Members :	**Prof. Dr. Abdurrahman SATMAN** İstanbul Technical University	....
	Prof. Dr. Ayşe Kaşlılar ŞİŞMAN İstanbul Technical University	....

Date of Submission : 15 October 2015
Date of Defense : 26 October 2015

To my wonderful parents and loved ones,

FOREWORD

My immense gratitiude goes to my thesis supervisor, Asst. Prof. Dr. İ. Metin Mıhçakan, for his invaluable guidance and constructive pointers.

I am highly indebted to Assc. Prof. Dr. İnanç Ö. Türeyen, for providing his Variable-Rate Non-Isothermal Simulation Code to complement my work, and spurring me on with vital input and pep talks.

I profoundly acknowledge Prof. Dr. Abdurrahman Satman, who has been pivotal at every stage in my work, with his incredible insights in my topic and for his painstaking efforts at reviewing the depth of the thesis.

Finally, my inestimable thanks goes to all my teachers, from nursey till date, who have inculcated in me academic discipline and work ethics, especially the amazing teaching staff of the Department of Petroleum and Natural Gas Engineering, at Istanbul Technical University.

October 2015 Suleman SALIA

TABLE OF CONTENTS

NOMENCLATURE

C_p : specific heat capacity
GEA : Geothermal Energy Association
h : enthalpy
k : permeability
L : characteristic length
P : volumetric average pressure
Q : thermal energy influx
T : temperature
t : time
USGS : United States Geological Survey
u : internal energy
V : reservoir bulk volume
w : production rate

Greek Symbols
ø : reservoir porosity
α : recharge constant
β : thermal expansion coefficient
κ : reservoir storage capacity
μ : viscosity
η : efficiency
γ : conduction index
ρ : density

Subscripts
a : aquifer
c : cross-sectional area
i : initial
in : input
inj : injection
jl : tank j_l
m : rock matrix
o : initial conditions
out : output
r : rock
ri : reinjection
ss : steady-state pressure
t : total reservoir (fluid and formation)
w : water
w,inj : injected water

LIST OF TABLES

Page

LIST OF FIGURES

Page

PERFORMANCE OF A GEOTHERMAL RESERVOIR UNDER UNITIZED AND COMPETITIVE UTILIZATION CONDITIONS

SUMMARY

Population growth and rising living standards remain as two of the key drivers for the increase of energy demand. Towards meeting such demand, as the technological advancements are crucial for diversifying energy sources, the adoptation of proper management strategies might be necessary for the efficient capacity development in existing sources.

Geothermal energy, classified as a renewable energy resource is playing a vital role in this pursuit because the production system is able to sustain production levels over long periods. The longevity of production can be secured and sustainable production can be achieved, by using moderate withdrawal rates, while considering the local resource characteristics.

A geothermal reservoir is indivisible by nature and so unregulated development of straddled leases overlying a reservoir, results in physical waste and under-utilization of resource, economic waste, environmental hazards, and inefficient resource management. The solution put forward to tackle this problem is unitization, which is defined as the voluntary or involuntary agreement by working interest owners of separate leases overlying the same reservoir to exploit and operate the resource as a cooperative and coordinated joint body under a designated operator. This concept delivers sustainable and efficient resource management, economic opportunities, and environmental benefits.

The objective of this thesis concerns reservoir behaviour under production with time, where two leases of different reservoir temperatures are operated under competitive and cooperative development strategies, and coming out with the optimum development design to generate 20 MW_e power. The study incorporates two stages. The first stage dwells on the comparison of reservoir behaviour under production with respect to time for competitive and cooperative utilization schemes. Reservoir pressure and reservoir temperature are the benchmarks for the analysis. The second stage is about the design of the appropriate development approach for a reservoir shared by two leases, assuming a constant electricity generation capacity throughout the project life.

The lumped parameter modelling is an analytical technique used for projecting the pressure response of a geothermal system to extraction. Non-isothermal tank model is selected as the tool to account for significant temperature changes associated with marked differences between recharge temperature and reservoir temperature, variations resulting from injection operations, and decrease in reservoir temperature due to production of fluids.

Three hypothetical cases of one-tank and two-tank models are proposed and analysed to study reservoir pressure and reservoir temperature behaviour relative to fluid production and time, with reinjection, under competitive and cooperative management of the two leases for constant electricity generation. The cases are set as, (a) Case 1: competitive approach with two leases, (b) Case 2: cooperative approach with unitized two leases, (c) Case 3: cooperative approach with unitized two leases (production in one lease and reinjection in other lease).

The assumptions made in this study are, (i) arbitrarily chosen reservoir rock and fluid properties in both leases, (ii) constant electricity generation from binary power plants, (iii) a binary power plant with 10 MW_e electricity generation capacity is installed on each competitive geothermal lease of different reservoir temperatures; or a binary power plant with 20 MW_e electricity generation capacity is installed on the unitized leases, (iv) temperature of the recharge (aquifer) and its connected Lease 1 are equal at 180°C in all cases, (v) reservoir temperature in Lease 2 is 160°C, and (vi) project design life is limited to 10,000 days for all cases.

The significance of this thesis is emphasized on selection of the most suitable development approach for a reservoir utilized by two straddled leases of different working interest owners. All the cases are evaluated in terms of the variation in average reservoir pressure, average reservoir temperature, net heat produced, and thermal efficiency of the power plant.

Out of the three cases investigated the unitized approach, in which production is from Lease 1 and reinjection in Lease 2, is found to be the desired mode of operation to feed the 20 MW_e capacity binary plant for the purpose of electricity generation. This case works best, because of well coordinated and informed technical decisions on appropriate well planning, based on extensive integrated data. Hot fluid zones are identified for production and are well separated from cooler regions, in which reinjection wells are to be located. The purpose of proper location of wells is to achieve the most efficient and sustainable energy production. As the reservoir section under Lease 1 is directly connected to the recharge source, from which the reinjection well is located far away in Lease 2, replenishment of produced fluids is at an adequate rate ensuring high average reservoir pressure. Locating the reinjection wells at a safe distance from the production wells in Lease 2, the temperature of the hot water zone is kept under control. Thus, the net heat produced would be very favourable, since the reinjected fluid is channelled through the reservoir section under Lease 2 to ensure minimal drop in temperature of the reservoir section under Lease 1, which enjoys hot liquid influx from the infinite size recharge source (aquifer). Case 3 also experiences the least drop in thermal efficiency of the binary power plant by the end of the design life.

It can be concluded that the owners of straddled leases should be encouraged or imposed on to act in a cooperative strategy for an unitized management of land, geothermal energy, any heat or energy source surrounding the geothermal waters, and ecosystem to derive maximum benefits for all stakeholders and safeguard public interests.

BİR JEOTERMAL REZERVUARIN BİRİMLEŞTİRİLMİŞ VE REKABETÇİ YARARLANMA KOŞULLARI ALTINDAKİ PERFORMANSI

ÖZET

Nüfus artışı ve yükselen yaşam standartları enerji talebine olan artışın yönlendirici unsuru iki olmayı sürdürmektedirler. Bu talebin karşılanmasına yönelik olarak enerji kaynaklarının çeşitlendirilmesinde teknolojideki ilerlemelerin can alıcı önemi olduğu kadar, var olan kaynakların kapasitelerinin etkin geliştirilmesinde uygun yönetim stratejilerinin uyarlanması gerekli olabilir.

Yenilenebilir enerji kaynağı olarak sınıflandırılan jeotermal enerji, bu arayış içinde yaşamsal bir rol oynamaktadır; çünki sistem üretim düzeylerini uzun dönemler boyunca koruyabilmektedir. Eldeki kaynağın özelik ve niteliklerine göre ortalama olarak nitelenebilecek çekiş debileri ile üretim düzeyinin korunması ve üretimin uzun ömürlü olması sağlanabilir.

Bir jeotermal rezervuar doğası gereği bölünemez ve böyle bir rezervuar üzerinde farklı işletilen komşu ruhsatların kuralsız geliştirilmeleri yararlanılan kaynağın fiziksel ziyanı, ekonomik zarar, çevresel sorunlar ve etkinlikten uzak kaynak yönetimi ile sonuçlanır. Bu sorunun üstesinden gelmek için öne sürülen çözüm, birimleştirmedir. Birimleştirme, aynı rezervuar üzerinde yer alan ayrı ruhsatların işletme payı sahiplerinin kaynağı gönüllü veya gönülsüz bir antlaşma ile, paylaşımcı ve eşgüdümlü bir oluşum halinde, belirlenmiş bir işletmeci aracılığı ile kullanmaları ve işletmeleri olarak tanımlanır.

Bu tez çalışmasının amacı, farklı rezervuar sıcaklıklarına sahip iki ruhsatın rekabetçi ve paylaşımcı işletim koşulları altında 20 MW güç üretebilmeleri için en uygun biçimde geliştirilmelerini tasarlamak üzere, zamana bağımlı üretim koşullarında rezervuarın davranışını ortaya koymaktır. Bu çalışma iki aşamayı kapsamaktadır. Birinci aşama, rekabetçi ve paylaşımcı yararlanma planları için zamana bağlı olarak yapılan üretimde rezervuar davranışını karşılaştırma üzerinde durmaktadır. Burada, rezervuarın basıncı ve sıcaklığı analizin kıstaslarıdır. İkinci aşama ise, proje yaşamı boyunca durağan bir elektrik üretim kapasitesi varsayımı ile, iki ruhsat tarafından paylaşılan bir rezervuarın gerektiği gibi geliştirilmesine yaklaşım tasarımı üzerinedir.

Boyutsuz LP (lumped parameter) modellemesi, bir jeotermal sistemden akışkan çekilmesi ile sistemin gösterdiği basınç davranışını yansıtmak için de kullanılan çözümsel (analitik) bir tekniktir. Bu modellemede eşısıl (izotermal) olmayan tank modelinin araç olarak seçilmesiyle, rezervuar ve beslenme sıcaklıkları arasındaki belirgin farklara bağımlı dikkate değer sıcaklık değişimleri, enjeksiyon işlemleri sonucu olan değişimler ve rezervuar sıcaklığında akışkan üretiminden kaynaklanan düşüş açıklanabilmektedir.

Durağan elektrik üretimi için iki ruhsatın rekabetçi ve paylaşımcı yönetim koşulları altında, üretilen akışkanın geri basılması da dikkate alınarak, akışkan üretimi ve

zamana göre rezervuarın basınç ve sıcaklık davranışını araştırmak üzere, bir tank ve iki tank modellerini içeren üç hipotetik durum önerilmiş ve analiz edilmiştir. Bu durumlar (a) Durum 1: iki ruhsatlı rekabetçi yaklaşım, (b) Durum 2: birimleştirilmiş iki ruhsatlı paylaşımcı yaklaşım, (c) Durum 3: birimleştirilmiş iki ruhsatlı paylaşımcı yaklaşım (bir ruhsatta üretim ve diğer ruhsatta geri basma) olarak belirlenmiştir.

Bu çalışmadaki varsayımlar, (i) her iki ruhsat için de keyfi olarak seçilmiş kayaç ve akışkan özelikleri, (ii) çift-çevrim (binary cycle) güç santrallarından durağan elektrik üretimi, (iii) rezervuar sıcaklığı farklı ve rekabetçi her bir ruhsat üzerine kurulmuş, 10 MW_e elektrik üretim kapasiteli bir çift-çevrim güç santralı; veya birimleştirilmiş ruhsatlar üzerine kurulmuş 20 MW_e elektrik üretim kapasiteli bir çift-çevrim güç santralı, (iv) beslenme kaynağı (akifer) ve bağlı olduğu Ruhsat 1 altındaki rezervuar kesiminin sıcaklıkları tüm durumlarda eşit ve 180°C, (v) Ruhsat 2 altında bulunan rezervuar parçasının sıcaklığı 160°C, ve (vi) proje tasarım ömrü tüm durumlar için 10,000 gün ile sınırlı olarak sıralanmaktadır.

Bu tezin anlamlılığı, işletme payı sahipleri farklı iki komşu ruhsatın yararlandığı bir rezervuar için en uygun geliştirme yaklaşımının seçiminde vurgulanmıştır. Dikkate alınan tüm durumlar ortalama rezervuar basıncı, ortalama rezervuar sıcaklığı, üretilen net ısı ve güç santralının ısıl verimindeki değişimler bakımından değerlendirilmiştir.

İrdelenen üç durumdan üçüncüsü olan, üretimin Ruhsat 1'den ve geri basımın Ruhsat 2'den yapıldığı birimleştirme yaklaşımı, elektrik üretimi amacıyla 20 MW_e kapasiteli çift çevrim santralının beslenebilmesi için istenen işletim şekli olduğu bulunmuştur. Bu durumun en başarılı işlemesinin nedeni, en uygun kuyu planlanmasının kapsamlı ve tümleşik verilerle ve bunların iyi eşgüdümü ve bilgilerine dayalı teknik kararlarla yapılmasıdır. Sıcak akışkan bölgeleri üretim için belirlenir ve geri basım kuyularının konuşlanacağı daha serin kesimlerden gayet iyi ayrılabilir. Kuyuları uygun yerlere konuşlandırmanın amacı en verimli ve sürdürülebilir enerji üretimidir. Ruhsat 1'in altındaki rezervuar kesimi Ruhsat 2'de bulunan geri basım kuyusundan çok uzaktaki besleme kaynağına doğrudan bağlantılı olduğundan, üretilen akışkanların yerine gerekli debide olan dolum ortalama rezervuar basıncının yüksek kalmasını sağlar. Ruhsat 2 içinde geri basım kuyularının üretim kuyularından güvenli bir uzaklıkta konuşlanmasıyla, sıcak su kesiminin sıcaklığı denetim altında tutulur. Dolayısı ile, geri basılan akışkan Ruhsat 2 altındaki rezervuar kesimi boyunca kanallaşıp, sonsuz boyuttaki besleme kaynağından (akiferden) giren sıcak akışkandan yararlanan Ruhsat 1 altındaki rezervuar kesiminin sıcaklığında olası en düşük azalmayı güvence altına aldığından, net ısı üretimi çok olumlu düzeyde olur. Ayrıca Durum 3, tasarım ömrü sonuna kadar çift çevrim santralının ısıl veriminde en düşük azalmayı yaşar.

Sonuç olarak söylenebilir ki, komşu ruhsat sahiplerinin sahanın, jeotermal enerjinin, jeotermal suları çevreleyen herhangi bir ısı veya enerji kaynağının ve ekosistemin birimleştirilmiş yönetim ile paydaşlar için olası en büyük yararı türetmek ve toplum çıkarlarını korumak üzere, paylaşımcı bir strateji içinde birlikte hareket etmeleri için cesaretlendirilmeli veya buna zorlanmalıdırlar.

1. INTRODUCTION

Energy demand by the modern society has no boundaries, and this insatiable demand will not stop any time soon, even under the most optimistic energy-efficiency scenario. The momentum of population growth and rising living standards especially in the developing world means that the demand for energy will last for decades. There is therefore the dire need to diversify energy sources and increase efficiency and capacity development through technological advancements.

Geothermal energy is an underground resource that has been exploited for generations by early civilizations in countries like Turkey, New Zealand, Japan, and the United States for cooking, heating, and bathing. Numerous benefits and applications of geothermal energy have been realized, since the turn of the last century. It offers a valuable alternative to economical, renewable, and clean energy production, which is in line with environmental protection and better quality of life. Geothermal energy is a reliable source of baseload power which also offers modular, incremental development, and village power to remote sites. Development of this energy contributes to socio-economic growth through creation of direct and indirect employment opportunities and generation of revenue to governments and land owners. The Geothermal Energy Association (GEA), estimates that the industry employs 2.13 persons per Megawatt for governmental, administrative, and technical related jobs. GEA also estimates that per Megawatt basis, geothermal energy employs 19 times the reported onsite employment of wind or solar PV project, and 5 times the reported onsite employment for concentrating solar project (Geothermal Energy Association Issue Brief, 2015).

More importantly, it contributes to diversity in energy resources and, thus, conserves non-renewable fossil fuels. The cons of this energy are related to environmental and socio-economic impacts from operations. Residents close to geothermal power plants contend with noise associated with drilling and well testing as well as foul smell from emitted gases into the atmosphere. Tests have shown that although emitted gases from geothermal operations like hydrogen sulphide are detectable by the human nose, emissions are far less than health damaging concentrations. Notwithstanding, efforts have been made to reduce this discharge. Currently, advanced technological methods are capable of over 90 % removal of hydrogen sulphide carried with the geothermal fluid, either before the steam flow reaches the turbine or after it flows past the turbine (Rodriguez et al., 2014). Another hazard emanates from discharge of non-reinjected wastewater from operations into surface or subsurface water bodies. The high temperature of the spillage, which may carry contaminants like arsenic, mercury, and boron, poses risks to aquatic life and access to safe drinking water. This danger can be mitigated by redirecting wastewater of considerable heat value into commercial and district space heating as is being applied on the Svartsengi plant in Iceland where the hot wastewater is pumped at 80°C to 120°C after deaeration, to the district heating systems for communities on the Reykjanes Peninsula and the Keflavik Airport (Sagun, 1992). Spillage and leakage of drilling fluids, additives, rock cuttings from mud pits and sumps contribute to surface and subsurface water pollution. At the Geysers geothermal field in California, drilling waste is hauled either to the geothermal drilling mud and cuttings disposal area in Waste Management Unit or to the Class II Solid Waste Management Facility. Liquids are stored on-site or transported by vacuum truck to existing injection wells for reservoir pressure maintenence. Hazardous waste, solid and/or liquid, would be sampled out and hauled off-site by a licensed hazardous waste disposing firm (Environmental Management Associates, Inc., 2004).

Currently geothermal energy is harnessed for so many purposes under direct-use to boost aquaculture, greenhouse farming, food processing, industrial drying, balneology, residential and district heating and cooling.

There are conscientious and pragmatic efforts to boost application of this technology to improve energy balance of the world by geothermal resource-rich countries. It is the policy of the Government of Iceland to increase the utilization of energy resources and, hence, goverrnmental support was increased for new geothermal based heat utilities by 50% even though 9 out of 10 households are heated with geothermal energy (Ketilsson et al., 2015).

Application of this energy for direct-use or power generation, depends upon some key factors like estimated reservoir temperature, flow rate, fluid chemistry, potential markets, financing, and expected income to be generated (Lund, 2011).

Figures 1.1 and 1.2, show the distribution of global final energy consumption with relative contribution of geothermal energy, and the world primary energy supply by sources.

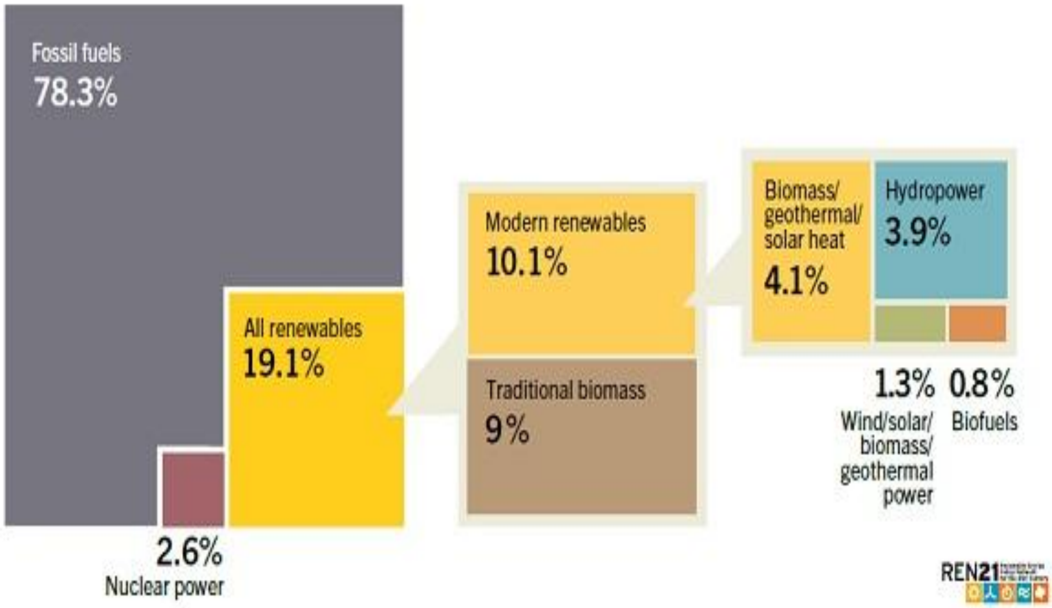

Figure 1.1 : Chart showing percentages of total global final energy consumption by source in 2013 (REN21, 2015).

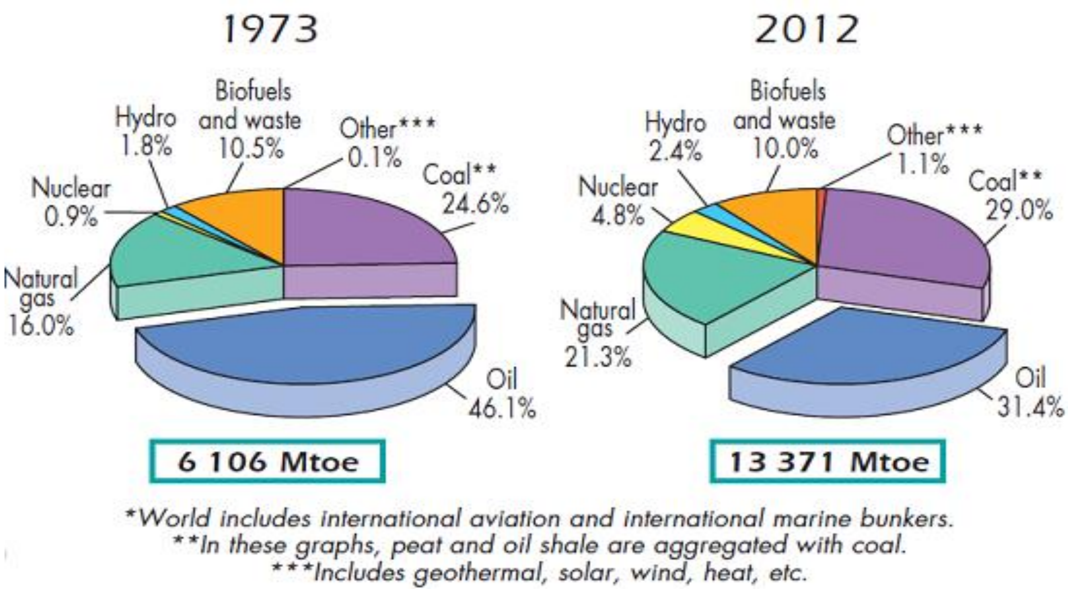

Figure 1.2 : Pie chart showing the comparison of the types of primary energy supply in the world for1973 and 2012 (International Energy Agency, 2014).

1.1. Literature Review

Some relevant definitions of terms in the context of geothermal energy, according to the United States Geological Survey (USGS), are as provided (Williams et al., 2011).

Geothermal resource base is all of the thermal energy in the earth's crust beneath a specific area, measured from the local mean annual temperature.

Geothermal resource is the fraction of the resource base at depths shallow enough to be tapped by drilling in the foreseeable future that can be recovered as useful heat economically and legally at some reasonable future time.

Geothermal reserve is defined as the identified portion of the geothermal resource that can be recovered economically and legally at present time using existing technology.

Geothermal reservoir is a subsurface system consisting of a large volume of hot water and/or steam trapped in porous and fractured hot rock underneath a layer of impermeable rock.

A schematic describing geothermal resource and reserve terminologies in the context of geology and economic viability is shown in Figure 1.3. Economic viability of geothermal resource is determined by drilling depth, fluid quantity and quality, and temperature of the resource.

Enhanced/Engineered geothermal system (EGS), comprises the portion of a geothermal resource for which a measurable increase in production over its natural state is or can be attained through mechanical, thermal, and/or chemical stimulation of the reservoir rock (Williams et al, 2011).

Though not commercially viable yet, EGS initiatives aim to demonstrate viability of creating a fracture network able to improve permeability and allow sufficient circulation of a liquid carrier for successful electricity generation. In a 2006 study, the Massachusetts Institute of Technology, MIT, identified the level of Federal commitment required for EGS and other unconventional geothermal resources to provide 100,000 MW_e of base load electric generation capacity by 2050 (MIT, 2006).

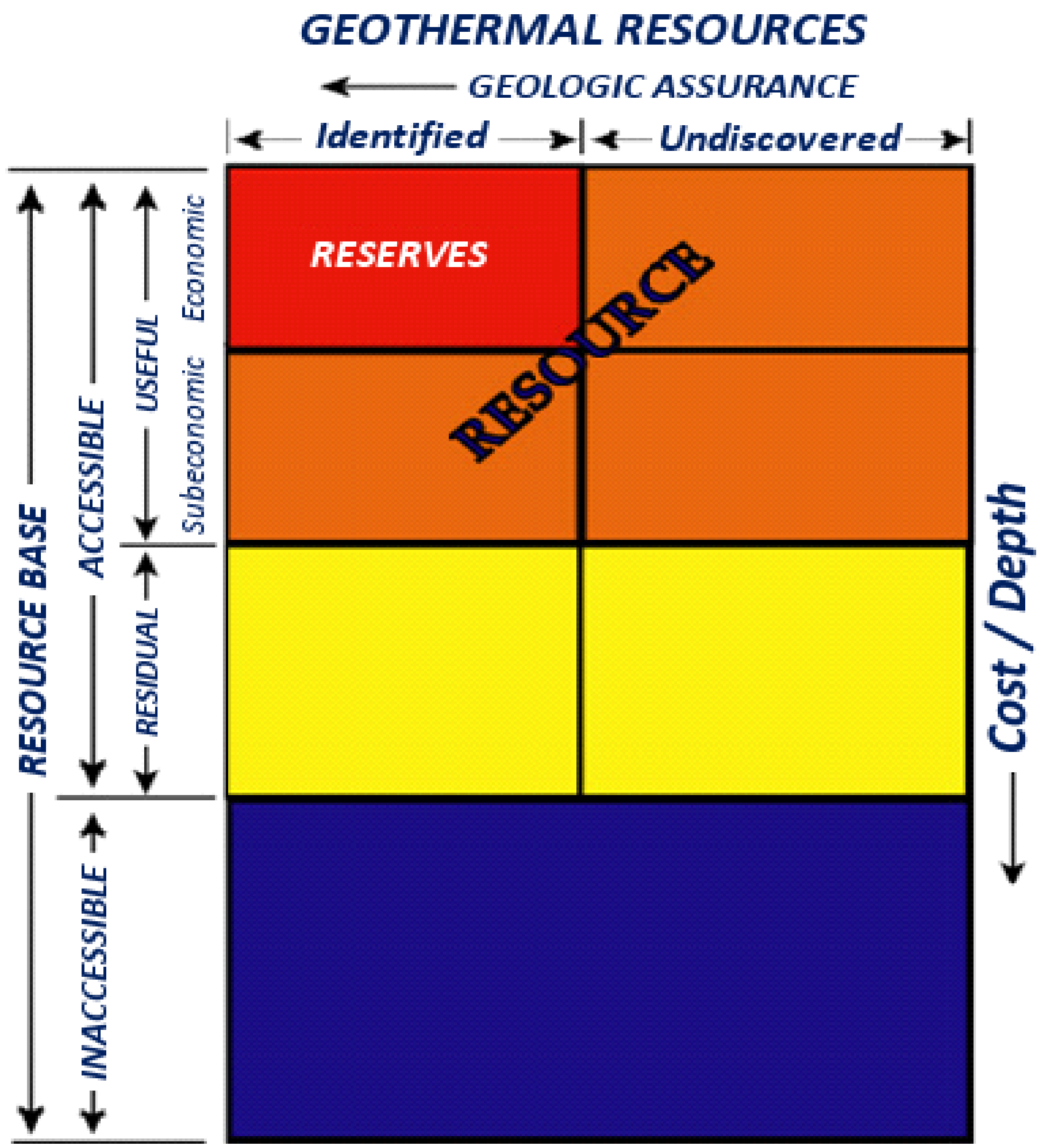

Figure 1.3 : McKelvey diagram representing geothermal resource and reserve terminologies in the context of geology and economic viability (Williams et al., 2011).

Geothermal system is any localised geologic setting where portions of the earth's thermal energy may be extracted from a circulating fluid and transported to a point of use. It comprises fundamental elements and processes, such as fluid and heat sources, fluid flow pathways, and a cap rock or seal, which are necessary for the formation of a geothermal resource. Figure 1.4 describes the schematic of a geothermal system.

On basis of physical state, geothermal reservoirs are sub-divided into three groups which are depicted in the pressure-temperature diagram for pure water showing the critical point and the boiling point curve in Figure 1.5.

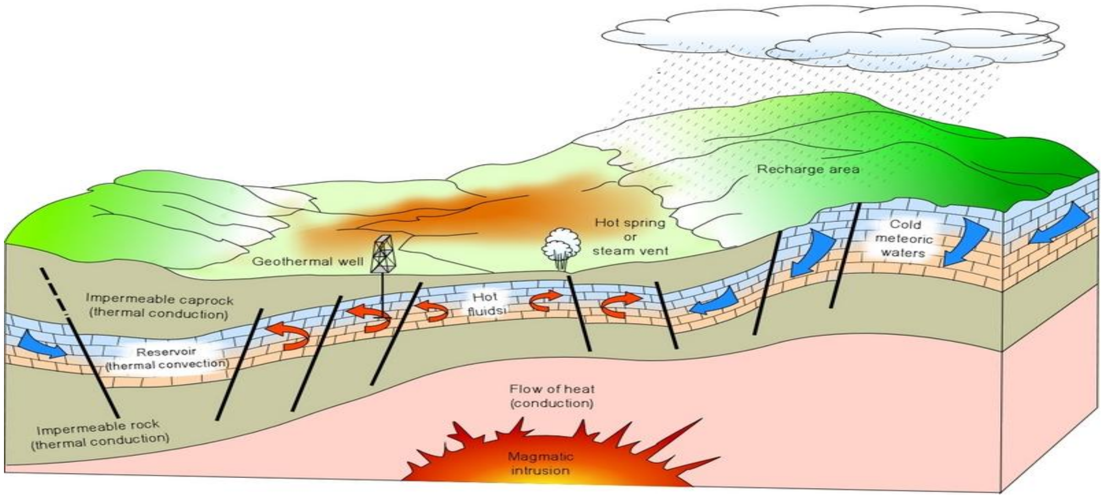

Figure 1.4 : Schematic of a Geothermal system (Liu et al, 2013).

I. Liquid-dominated geothermal reservoirs where the water temperature is at, or underneath the boiling point curve at the prevailing pressure. The water phase is the reservoir pressure control parameter.

II. Two-phase geothermal reservoirs in which the liquid and vapor phases co-exist and the pressure and temperature follow the boiling point curve.

III. Vapor-dominated geothermal reservoirs wherein the water temperature is at, or above the boiling point curve at the existing pressure. The vapor phase controls the reservoir pressure. In this type of reservoir, some water may be present.

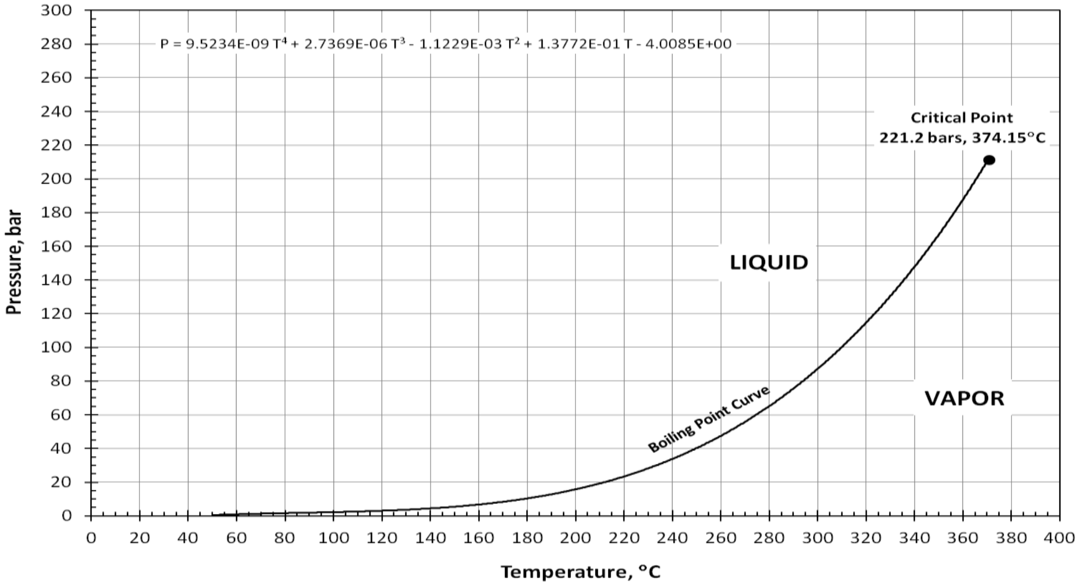

Figure 1.5 : Pressure-temperature diagram for pure water.

USGS classifies geothermal systems on basis of temperature into three categories (Muffler, 1979; Williams et al., 2008):

I. Low-temperature systems, having temperature values below 90°C; which are all liquid-dominated resources.

II. Moderate-temperature systems with temperature range between 90-150°C; most exclusively liquid-dominated.

III. High-temperature systems, with temperature values above 150°C; include both liquid- and steam-dominated resources.

Direct usage can be tapped from all the classes especially the lower end of the low-temperature resources. Viable electric power generation is best utilized from moderate- and high-temperature resources. Again, systems at the high end of low-temperature systems can also be tapped for electricity generation, provided adequately low temperatures are available for cooling working fluid in a binary power plant.

On the whole, a geothermal reservoir may exist in diverse conditions, with or without two phases, and with either a strong or weak natural recharge. Drive mechanisms which push the geothermal fluid to the producing well are predominantly through displacement by water when an active natural recharge is present, and the expansion of gas (steam and/or non-condensables such as carbon dioxide) in the two phase conditions. To a lesser degree, rock and water expansion also contribute as drive mechanisms.

Worldwide installed capacity for geothermal electricity generation is 12.635 GW_e generating 73,549 GWh of energy in over 20 countries by end of 2014 (Bertani, 2015). Turkey, which is one of the fastest growing geothermal electricity generation countries added 107 MW_e in 2014 increasing its installed capacity to 0.4 GW_e, with plans to boost this output to 1 GW_e by 2023 (REN21, 2015) . In direct-usage, Turkey had an installed capacity of 2.8 GWt generating 12.2 TWh by the end of 2014 registering it as the second highest in the world (REN21, 2015). Geothermal resource base between 0 and 3 km depth in Turkey and the capacity of identified geothermal sites have been determined to be 3.96 x 10^{23} J and 10,576 MW_t, respectively (Korkmaz et al., 2014).

The main bottlenecks facing a faster utilization of global geothermal energy are:

1. high upfront costs
2. investment risks and
3. technical challenges.

These challenges can be mitigated through the following interventions:

I. training and outreach educational programs
II. technological enhancements
III. economic incentives
IV. governmental support

1.2. Statement of Problem

Tremendous increase in global demand for energy has given geothermal energy a comparative drive relative to other energy resources. This development is putting a strain on geothermal resources in terms of license acquisitions to explore and develop reserves.

Just like in the oil and gas industry, license holders of leases reserve the right to explore, develop, produce, and utilize resources. To maximize revenue, land owners usually sell off tracts which straddle the same reservoir to different parties without being clear, on who among the lease owners has the definitive rights to develop the resource. Rule of capture relating only to extraction of geothermal fluid dominates, where no party is liable to drainage of resources from another property line and producing resource of another, so long as producing wells do not trespass nor regulations and statutes breached. These working interest owners endeavour to drill and produce competitively at high rates in the shortest time, leading to several damaging repercussions.

Geothermal reservoir is indivisible by nature and so unregulated development of straddled leases overlying a reservoir results in physical waste and under-utilization of resource, characterised by high rate of pressure decline and reduced total heat produced.

Improper placement of wells under competitive approach may lead to extraction of fluids in a cooler zone and so hot liquid in the hotter zone is deprived of driving force provided by the cooler liquid front. Again withdrawal of the colder liquid from the reservoir as a result of haphazard well placement fails to achieve intended heat recovery for utilization. Production in cooler region also creates a void which is replaced by hot fluid, thereby decreasing total heat content of the reservoir fluid. Competitive production reduces reservoir pressure such that gas evolves from the liquid phase which in turn restricts passage of the less mobile liquid.

There is enormous economic waste associated with this practice in the building of duplicate wells, pipelines, and surface facilities. Very high development and operational costs, which can be avoidable, are wasted in competitive exploitation. This development approach leads to inefficient and unsustainable management, and demoralization of markets and prices.

Decrease in ultimate recovery means countries get far less revenue and companies resort to dirty production tactics which sets up long and time-consuming legal battles, when such acts are discovered by aggrieved parties.

Increase in environmental and ecological interference and degradation arises due to construction of excessive roads and well pads. Generated noise and increased emissions from geothermal plants in nearby residences, attract unfavourable public displeasure.

The solution proffered to tackle this problem is unitization, which is defined as the voluntary or involuntary agreement by working interest owners of separate leases overlying the same reservoir to exploit and operate the resource as a cooperative and coordinated joint body under a designated operator. The concept will be discussed in the subsequent chapter.

This thesis incorporates two phases. The first section, examined in chapter 3, dwells on comparison in reservoir behaviour under production with respect to time, between competitive and cooperative production schemes. Average reservoir pressure and average reservoir temperature are the benchmarks for the analysis.

The second phase discusses the design of the appropriate development approach for a reservoir shared by two leases, and assuming a constant electricity generation capacity throughout a project life. This premise is chosen to address the misleading impression that constant geofluid production rate can suffice for constant capacity electricity generation by a power plant. The reservoir performance indicators adopted for this study are the average reservoir pressure, average reservoir temperature, net heat produced, and the thermal efficiency of the binary power plant. This section is explored in chapter 4.

In the past, power generation from geothermal resources had been limited to resources above 180 °C. Recent advancements in the binary cycle technology, makes it possible to utilize low-temperature geothermal fluids around 100 °C for power generation, hence increasing the number of potential locations and opportunities. As such, designing an optimum development scheme for electricity generation, from a reservoir shared by two leases, is of utmost benefit and importance.

The non-isothermal lumped parameter model will be employed to simulate reservoir profile, which will then be compared to analytical expressions for clarity.

2. UNITIZATION

Production from geothermal fields depletes reservoir pressure and energy at a faster rate than it is replenished by pre-production flow. Without pressure and energy maintenance mechanisms, fields cannot be exploited at rates necessary to operate installed capacities of power plants on a continuous basis over the design life, thus becoming unsustainable.

Sustainability can be explained as the ability to economically maintain the commercial capacity, over the amortized life of a geothermal and/or power project, by taking practical steps such as reinjection and make-up well drilling, to compensate for resource degradation in terms of pressure drawdown and/or cooling (Sanyal, 2005). Sustainanable management is also defined as the sustaining of the potential of natural and physical resources to meet the reasonable foreseeable needs of future generations; thus sustainably managing a region's geothermal resource should be preferred to managing individual systems' sustainability (Tureyen et al., 2015). The owners of straddled (multiple) leases over a reservoir should, therefore, be encouraged and/or imposed on, to act in a cooperative strategy. It involves the integrated management of land, geothermal energy, any heat or energy source surrounding any geothermal water, and ecosystems. Sustainable management of the geothermal resource requires knowledge of the complex physical structures and interactions within the systems (Satman, 2010).

Unitization, as defined earlier, involves an agreement by working interest owners of separate tracts overlying the same reservoir, to exploit and operate the resource as a cooperative body under a designated operator. Unitization is a conservation measure that tends to promote economic development of geothermal energy which must be utilized near the producing area, and to prevent waste of the resource (Cargill and Conover, 1978; Lueck and Schenewerk, 1996; Oliver and Umpleby, 1930; Russel et al., 1972). It is a concept which was encouraged and championed in the oil and gas industry in the late 1920’s by various organizations and agencies and later regulated by state conservation statutes and by federal regulation in the United States (US), to instill order, and protect public interests in the otherwise haphazard industry. Similarly this strategy has been translated to the geothermal industry notably in a few states in the US. Unitization is yet to be standardised and enforced in most geothermal energy producing countries.

In certain states in the US, where geothermal unitization has been executed, the application has been drawn from experiences in unitization of oil and gas fields. Similarities that cut across both industries are the use of identical terminologies, concepts, and processing steps. However geothermal units have completely different statutes, regulations, policies, and model forms.

Out of the multitude of identified geothermal fields in Turkey, none has been unitized, although several straddle leases overlie the same reservoir. Left unchecked, competitive development of geothermal fields could trigger flush production and damaging interference effects between neighbouring leases with associated legal feuds. Thus unitization provides a solution to regulate license holders and ensure sustainable resource development for public benefit.

The main objective of coordinated operation of geothermal resource is to maximize heat recovery and ensure efficient use of the energy at the least cost by appropriate placement of wells. Comparison between the competitive and cooperative field developments are illustrated in Figure 2.1.

Unitization offers effective and accountable resource management, as well as responsible, efficient and secure resource development. Efficient use and development of the geothermal resource involves the well regulated extraction from the resource and the efficient utilization of what is extracted. This necessitates for

I. integrated and cooperative development of a whole system,

II. absence of competitive extraction of data, fluid, or energy from a geothermal system,

III. effective and efficient monitoring and evaluation of the resource state,

IV. conditions that reduce environmental and investment risk.

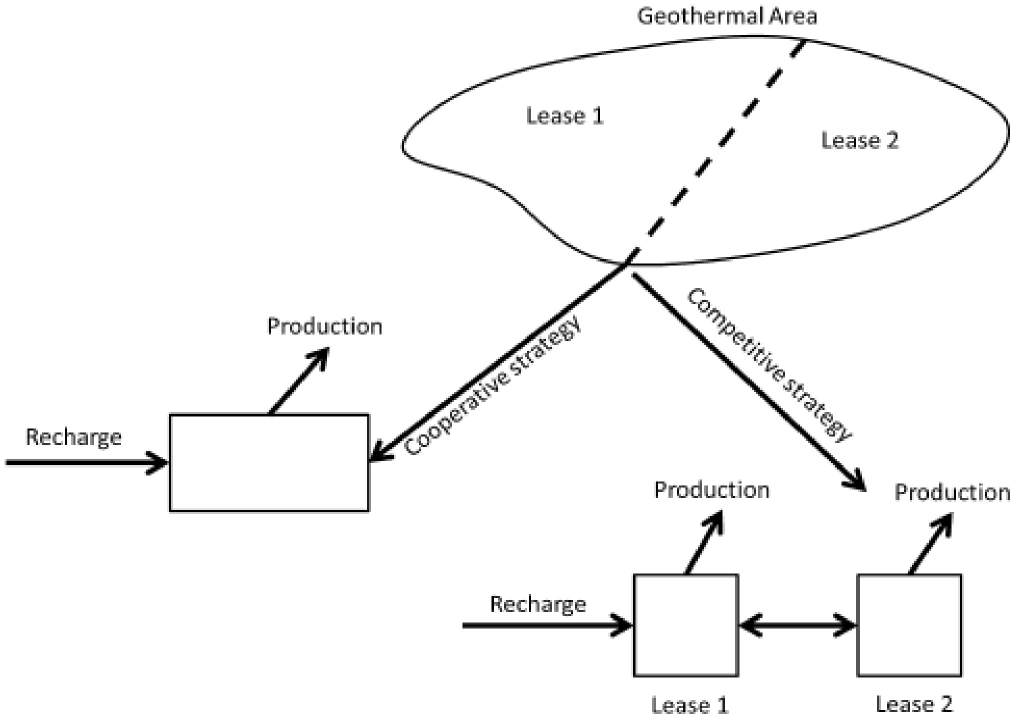

Figure 2.1 : Comparison of competitive and cooperative field operations (Tureyen et al., 2015).

Production rate of a well drains a comparable volume proportional to the recoverable fluid and heat below a lease. To attain equity in a unitized reservoir, each lease should be permitted to produce a quantity of heat proportional to the remaining recoverable reserves relating to the lease. As such, the needed formula should be embedded with a recovery factor indicating the capacity of the drilled wells to recover the geothermal fluid and heat beneath the lease.

Unitization offers numerous benefits, some of which are as follows.

Geothermal resource benefits: Coordinated effort aimed at optimum pressure management ensures sustainable production of the resource leading to far less reduced waste compared to competitive lease operations. Under the control of a single operator maximum recovery of the resource is achieved through appropriate well spacing and the use of enhanced recovery and recycling, as needed.

Economic benefits: Power plants and their peripheral facilities are installed in a unit area instead of several of those in separate leases. Units also enjoy reduction in operational costs in economy of scale. The number of production and injection wells is balanced for the resource.

Environmental benefits: There is less disturbance and also low emissions in the environment which improves quality of life in residential areas close to geothermal power plants. Unitized production also minimizes interference with ecological systems because fewer well pads and roads are constructed.

Control: Cooperative development offers relative ease in administration of leases under a single operator. Sales contract is unified which streamlines the sale of geothermal resource.

Lease Benefits: Operations anywhere within the unit favours all committed leases ensuring equity and fairness. A right-of-way is not required for activities that occur across lease lines, which saves considerable operation time.

Definitions of some common terms in unitization concept are as follows (www.law.cornell.edu/cfr/text/43/3280.2, 30th August, 2015).

Unit Agreement – An agreement for the exploration, development, production, and utilization of separately owned interests in the geothermal resources made subject thereto, as a single consolidated unit without regard to separate ownerships, which provides for the allocation of costs and benefits on a basis defined in the agreement.

Unit Area - It is the area prescribed in the unit agreement as constituting the land logically subject to development under such agreement.

Unitized Land – The part of a unit area committed to a unit agreement.

Participating Area – The part of the unit area that is deemed to be productive from a horizon or deposit and to which production will be allocated in the manner described in the unit agreement.

Unit Contraction – This is a term of a unit agreement providing that the boundaries of the unit area will contract to the size of the participating area, by having those lands outside of the participating area removed.

The unit area should be contracted if additional unit wells are not drilled and completed within the time frame specified in the unit agreement.

Unitized Substances - Deposits of geothermal resources recovered from unitized land by operation under and pursuant to a unit agreement.

Unit Well – A well that is designed to produce or utilize geothermal resources in commercial quantities, drilled and completed, to the bona fide geologic objective specified in the unit agreement, unless a commercial resource is found at a shallower depth and located on the unitized land.

Minimum Initial Unit Obligation – The requirement to complete at least one unit well within the time frame specified in the unit agreement. If this requirement is not met the unit is deemed to be void as though it was never in effect.

Unit Operator – The person, association, partnership, corporation, or other business entity, designated under a unit agreement, to conduct operations on unitized land as specified in such agreement.

Working Interest – This refers to the interest held in geothermal resources or in lands containing the same by virtue of a lease, operating agreement, fee title, or otherwise, under which, except as otherwise provided in a unit agreement, the owner of such interest is vested with the right to explore for, develop, produce, and utilize such resources. The right delegated to the unit operator as such by the unit agreement is not regarded as a working interest.

Plan of Development – The document a unit operator submits for defining how the unit operator will diligently pursue unit exploration and development, to meet both initial and subsequent unit development and public interest obligations.

Public Interest – Operations within a geothermal unit resulting in diligent development, efficient exploration, production and utilization of the resource, conservation of natural resources, and prevention of waste.

Reasonably proven to produce – Sufficient demonstration, based on scientific and technical information, that leases are contributing to unit production in commercial quantities, or leases are providing reservoir pressure support for unit production.

Adequate evidence which supports implementation of unitization should be expertly gathered and analysed with participation from all stakeholders. Data are collected from several disciplines including geothermal reservoir engineering, geology, socio-economic analysis, law, and environmental impact assessments.

3. TANK MODELS

Pressure decline in geothermal reservoirs is a response to geothermal fluid production. The rate of pressure decline is driven by three main factors which are

1. rate of production and/or reinjection,
2. size and properties of the geothermal system,
3. recharge characteristics of the system.

In this work a comparative analysis is performed on reservoir performance indicators of reservoir pressure and reservoir temperature, to examine development schemes under competitive and cooperative reservoir operations.

3.1. Comparative Analysis: Competitive and Cooperative Reservoir Operation

The benchmark for comparison will be based on average reservoir pressure behaviour of leases owned by two license holders and that of a unitized field. The pressure drop is chosen to be the reference point because pressure drawdown is widely regarded as a sustainability measurement tool in the geothermal industry.

Consider a geothermal system comprising of a reservoir and a recharge source (labelled as a 1-tank reservoir) initially at equilibrium at time, t = 0. Pressure behaviour of this system will be analysed as a function of production time under the conditions of constant production rate and constant recharge pressure, expressed as;

$$\Delta \mathrm{P} = \frac{\mathrm{w}}{\alpha}\left[1 - \exp\left(-\frac{\alpha t}{\kappa}\right)\right] \tag{3.1}$$

Equation 3.1 with respect to reservoir pressure:

$$\mathrm{P} = P_i - \frac{\mathrm{w}}{\alpha}\left[1 - \exp\left(-\frac{\alpha t}{\kappa}\right)\right] \tag{3.2}$$

$$\kappa = V_r \phi \rho C_t \tag{3.3}$$

where;

P	Volumetric average reservoir pressure
P_i	Initial pressure of recharge source
w	production rate
$\boldsymbol{\alpha}$	recharge constant
t	time
κ	reservoir storage capacity
V_r	reservoir bulk volume
Ø	reservoir porosity
ρ	density of reservoir fluid
C_t	total reservoir compressibility (fluid and formation)

The Schilthuis steady-state water influx equation is applied to describe pressure behaviour at late- time of the reservoir life for the 1-tank model:

$$\Delta P_{SS} = \frac{w}{\alpha} \tag{3.4}$$

Where ΔP_{SS} represents the steady-state pressure drop, $(\Delta P_{SS} = P_i - P)$. This implies that pressure decline is dependent on recharge constant, $\boldsymbol{\alpha}$, but independent of reservoir storage capacity κ, and proves that stabilization occurs at a value determined by a balance with the recharge.

Sarak et al. (2005) and Satman et al. (2005) have done comprehensive work on multiple tank models to demonstrate an aquifer and a set of vertically divided reservoirs. A schematic of various tank models is shown in Figure 3.1.

Terms in Figure 3.1 are;

w	net mass withdrawal rate
w_a	recharge rate from recharge source to reservoir tank
ρ_w	density of water in the reservoir
ρ_a	density of water in the aquifer

The net mass rate (*w*) is defined as the difference between the production and reinjection rates.

For the 1-Tank model, reservoir is produced at a mass rate of *w* and supplied with water by a recharge source at a constant pressure of P_i.

With the 2-tank model, the first tank on the extreme right hand side, represents the reservoir from which production or reinjection takes place. The second tank which is connected to the first tank (reservoir) illustrates the outer part of the system (aquifer) which feeds the reservoir. Withdrawal of hot water results in pressure decline in both tanks implying that the entire system is indivisible by nature.

The third schematic illustrates a 2-tank model where the reservoirs (a shallow and a deep reservoir) are interconnected and both producing at w_1 and w_2 respectively; both reservoirs are replenished by natural recharge sources.

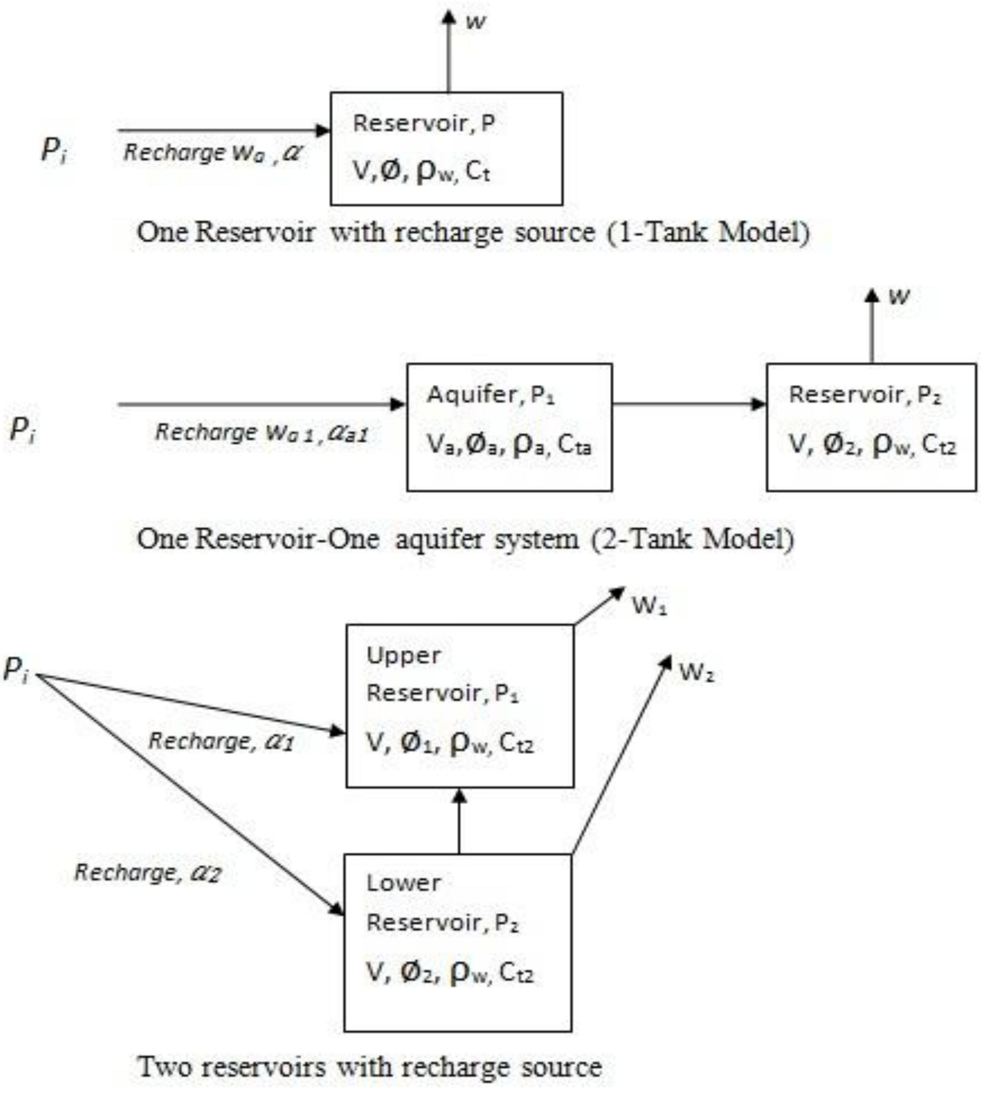

Figure 3.1 : Schematics of 1-Tank and 2-Tank models (Tureyen and Satman, 2013).

Pressure drawdown for the tank models which are all at a constant production rate are shown in Figure 3.2.

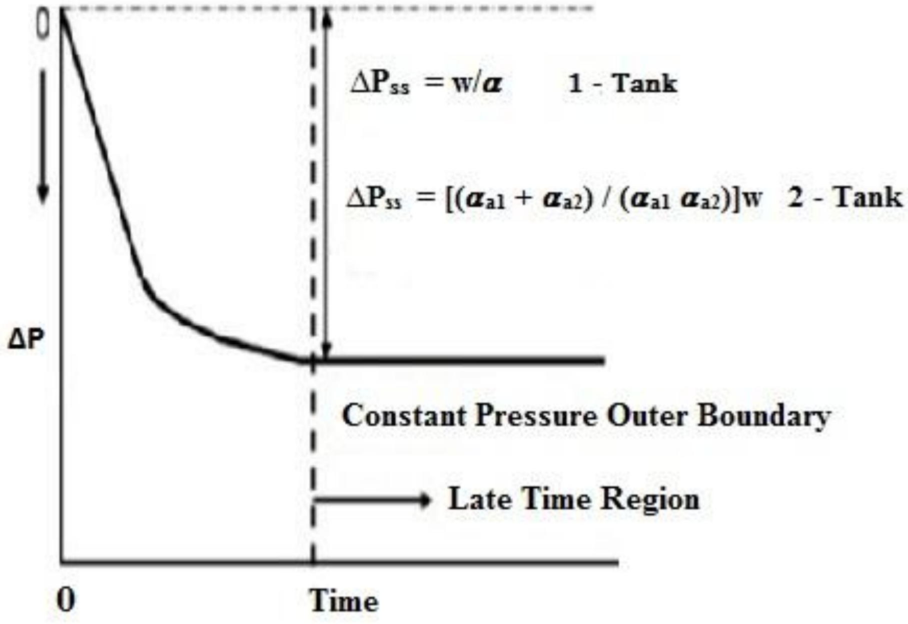

Figure 3.2 : Steady-state pressure behaviour of tank models at late-time.

The 1-Tank model represents cooperative unit management of a reservoir by multiple license holders.

Consider the 2-Tank model with one recharge source as an illustration of a competitive reservoir development of two adjacent leases overlying the same reservoir operated by different lessees. The steady-state pressure drop equations for the two leases will respectively be:

$$\Delta P_{SS1} = \frac{w_1 + w_2}{\alpha_1} \tag{3.5}$$

$$\Delta P_{SS2} = \Delta P_{SS1} + \frac{w_2}{\alpha_{12}} \tag{3.6}$$

where;

α_{12} inter-lease recharge constant defined by:

$$\alpha_{12} = \frac{k A_C \rho_W}{\mu \Delta L} \tag{3.7}$$

where

k reservoir permeability

A_c cross-sectional area of recharge

ρ_w density of water

μ viscosity of water

ΔL characteristic length (reservoir half length for edge water influx)

As has been shown, competitive reservoir management is biased against one lease since pressure drop of the first lease is added onto the pressure drop of the second lease.

However inclusion of temperature behaviour in both cases will give a much more detailed and comprehensive bases for comparison since temperature and heat recovery are equally essential in geothermal projects.

3.2. Non-Isothermal Tank Model

Reservoir modelling describes change in reservoir pressure as a function of time or cumulative fluid production, and serves as a fundamental basis of subsurface fluid study of which geothermal reservoir is no exception. It provides critical data like rate of pressure decline, effects of recharge and reinjection, production capacity, and interference effects of production between tracts straddling a common reservoir.

The most common approach used to model geothermal reservoir behaviour is the fully discretized numerical model or the lumped parameter model (Bodvarsson et al., 1986), which is an analytical technique for modelling the pressure response of a geothermal system to extraction.

The model considers the entire geothermal system as two blocks; one block represents the recharge source or aquifer whilst the other block illustrates the reservoir. The reservoir is represented as a network of storage tank and flow conductors. The model relies on mass balance and energy balance. Non-isothermal condition is considered to account for significant temperature changes associated with marked differences between recharge temperature and reservoir temperature, and variations resulting from injection operations. Non-isothermal condition is relevant even in closed systems which do not incorporate reinjection because, continual production of fluids leads to decrease in temperature.

Lumped parameter model is a simple application for forecasting sustainability and estimating reservoir pressure at a lower cost and in less time. It relies on a relatively smaller number of parameters compared to the numerical model and so offers shorter run times. It is preferable at the development stage when there is little information about the reservoir.

Lumped parameter models generally ignore the internal structure of the system (Grant, 2013).

The drawbacks of this model are that it provides limited ability to represent field geometry, does not consider fluid flow within the reservoir, and also neglects spatial variations in thermodynamic conditions and reservoir properties. As a result, it can neither match average enthalpy and non-condensable gas content of the produced fluid nor simulate phase and thermal fronts (Bodvarsson et al.,1986).

Tureyen and Akyapi (2011) developed a generalised non-isothermal tank model for a single-phase liquid water and rock system. It considers variable-rate non-isothermal flow based on mass balance and an energy balance which considers both convection and conduction heat influx. It is chosen in this study to analyse pressure and temperature behaviour in a straddling reservoir subjected to competitive operation as against a unitized development.

Under this model, the system is composed of an arbitrary number of tanks, N_t. Each tank consists of water and rock components. Figure 3.3 demonstrates the properties of any arbitrary tank i.

The illustrated tank i above has a bulk volume V_{bi}, temperature T_i, pressure P_i and porosity $ø_i$. Here any tank i (i = 1,2,3,.., N_t,) can make random number of connections with other tanks. Let N_{ci} represent total number of connections tank i can make. Connecting tanks are characterised by j_l, where l = 1,2,3,... N_{ci}. This appplication allows for both production out of and injection into tank i. Production is at a fixed mass rate $w_{p.i}$ at reservoir temperature T_i and injection is also at a fixed mass rate $w_{inj.i}$ at temperature $T_{inj,i}$. By chosen convention, production $w_{p.i}$ is positive i.e. $w_{p.i} > 0$ whilst injection $w_{inj.i}$, is negative i.e. $w_{inj.i} < 0$.

From Schilthuis (1936), mass flow rate between any connecting tank j_l and tank i is given by:

$$w_{i,jl} = \alpha_{i,jl}\left(P_{jl} - P_i\right) \tag{3.8}$$

where;

$w_{i,jl}$ is the mass flow rate between tank i and tank j_l

$\alpha_{i.jl}$ is the recharge index i.e. mass flow rate per unit pressure drop assumed to be constant

P_{jl} is the pressure in tank j_l

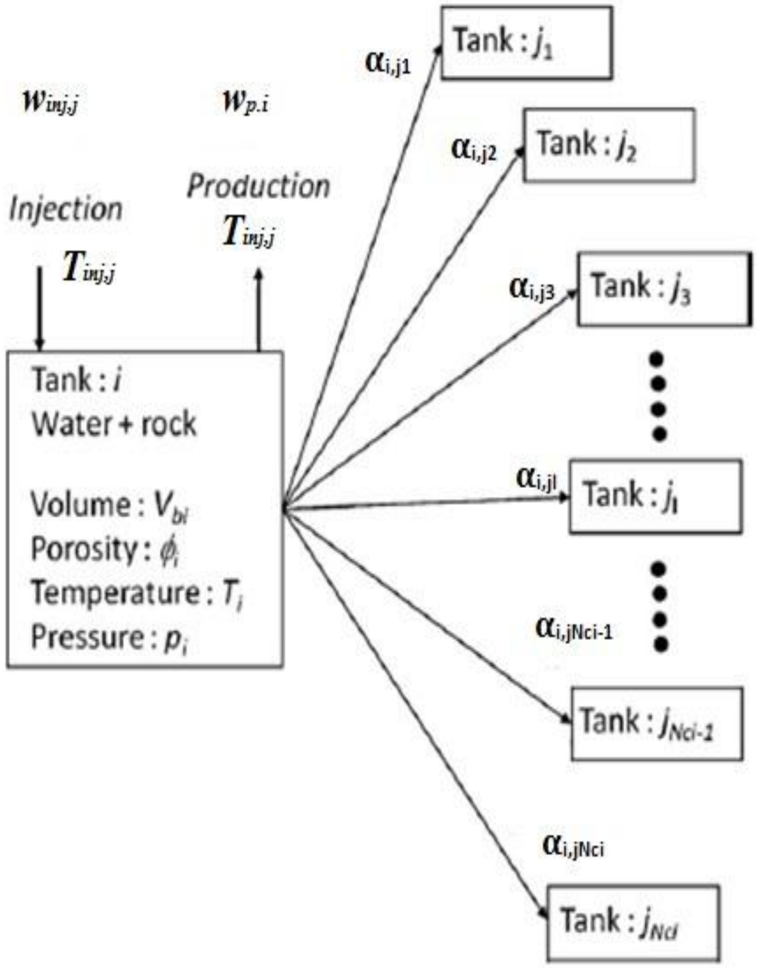

Figure 3.3 : Properties of the representative tank (tank *i*).

Conservation of mass for a single-phase liquid water and rock system under these assumptions can be given as:

$$V_{bi}\frac{d(\rho_{wi},\phi_i)}{dt}-\left[\sum_{l=1}^{N_{ci}}\alpha_{i,jl}(P_{jl}(t)-P_i(t))\right]+w_{p,i}(t)+w_{inj,i}(t)=0 \tag{3.9}$$

where

ρ_{wi} is density of water in tank *i* and *t* represents time.

It is assumed that porosity varies with time but bulk volume is assumed to be fixed during simulation. On the left hand side of Equation 3.9, the first term represents accumulation of mass in the tank, second term depicts mass influx from the connecting tanks, third term characterises production mass rate whilst the last term shows injection mass rate.

Energy balance involves both convection and conduction. Energy influx resulting from conduction is determined by;

$$Q = \gamma_{i,jl}\left(T_{jl} - T_i\right) \tag{3.10}$$

where;

Q energy flux

$\gamma_{i.jl}$ the conduction index depicting energy influx per unit temperature drop due to heat conduction

T_{jl} temperature of tank j_l

A local thermal equilibrium in tank *i* between liquid water in pore network and rock is assumed. Energy balance for the system is expressed as;

$$\begin{aligned}&\frac{d}{dt}\left[\left(1-\phi_i\right)V_{bi}\rho_{mi}C_{pmi}T_i + V_{bi}\phi_i\rho_{wi}u_{w,i}\right] + w_{inj,i}(t)h_{w,inj,i}\left(T_{inj,i,t},t\right) + w_{p,i}(t)h_{w,i}\left(T_i,t\right)\\&-\sum_{l=1}^{N_{ci}}\alpha_{i,jl}\left(P_{jl}(t)-P_i(t)\right)h_{\zeta} - \sum_{l=1}^{N_{ci}}\gamma_{i,jl}\left(T_{jl}(t)-T_i(t)\right) = 0\end{aligned} \tag{3.11}$$

For i = 1,2,3,..., N_t

where;

ρ_m density of rock matrix

C_{pm} specific heat capacity of rock matrix

u_w internal energy of water

h_w enthalpy of water

$h_{w,inj}$ enthalpy of injected water

heat transfer due to convection, h_{ζ} ;

$$h_\zeta = \begin{cases} h_{w,i}\left(T_i(t)\right) & if\ P_i \rangle P_{jl} \\ h_{w,jl}\left(T_{jl}(t)\right) & if\ P_i \langle P_{jl} \end{cases} \tag{3.12}$$

On the left hand side of Equation 3.11, the first term represents accumulation of energy in the rock and in the liquid water , second term depicts energy content of the injected water. The third term characterises energy content of the produced water, the fourth term represents the energy influx from the connecting tanks and the last term shows energy influx due to conduction. Enthalpy, internal energy, and density of water are calculated from the steam tables (ASME, 2006).

Change of porosity as a function of pressure and temperature is modelled using relationship developed by Onur et al. (2008):

$$\phi(P,T) = \phi_0\left[1 + C_r(P - P_0) - \beta_r(T - T_0)\right] \tag{3.13}$$

where;

ϕ_0 porosity of the tank at initial conditions ie. $\phi_0 = \phi(P_0, T_0)$

C_r compressibility of the rock

β_r thermal expansion coefficient of the rock

3.3. Model Runs

In order to test the efficiency of geothermal unit operations, modelling is performed using the non-isothermal model. Simulation will help in describing reservoir pressure and temperature behaviour to predict future reservoir characteristics, which will greatly improve reservoir management. Three production scenarios each having a design life of 10,000 days, are created by assuming a hypothetical geothermal field assigned average model parameters shown in Table 3.1.

1. 1 tank - 1 recharge source model
2. 2 tank - 1 recharge source model
3. 2 tank – 2 recharge source model

Table 3.1 : Rock and fluid properties of a hypothetical geothermal reservoir for no renjection considered.

Parameter	1 Tank - 1 recharge source	2-Tank - 1 Recharge source		2 Tank – 2 Recharge source	
		Tank 1	Tank 2	Tank 1	Tank 2
Bulk volume of rock, m^3	1.0×10^9	0.5×10^9	0.5×10^9	0.5×10^9	0.5×10^9
Specific heat capacity of rock, J/(kg-°C)	1000	1000	1000	1000	1000
Rock compressibility, 1/bar	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Initial Pressure of reservoir, bar	100	100	100	100	100
Initial temperature of reservoir, °C	150	150	150	150	150
Porosity, fraction	0.15	0.15	0.15	0.15	0.15
Density of rock, kg/ m^3	2600	2600	2600	2600	2600
Recharge constant, kg/(bar-s)	$\alpha_1 = 10$	$\alpha_1 = 10$	$\alpha_{1,2} = 10$	$\alpha_1 = 10$	$\alpha_2 = 10$ $\alpha_{12} = 10$
Recharge temperature, °C	100	100	100	100	100

3.3.1. 1 tank - 1 recharge source model

An illustration of this model is shown by the schematic in Figure 3.4. Let production rate be fixed at 200 kg/s for the production time of 10,000 days.

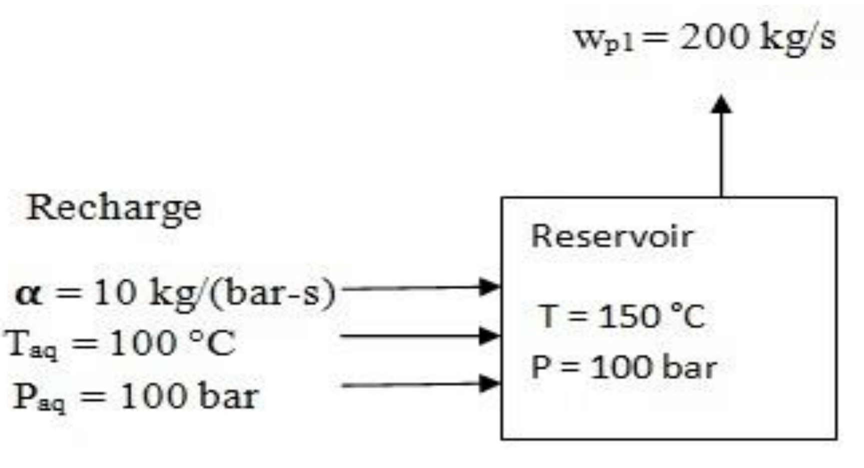

Figure 3.4 : Schematic of 1 tank – 1 recharge source model.

The 1-Tank model is a representation of agreed and coordinated unitized geothermal reservoir exploitation by two or more lease holders to a reservoir or a significant part thereof. Placement of wells is carefully chosen after comprehensive reservoir studies, to identify optimum hot fluid zones for production which are well separated from cooler regions, from which reinjection wells are to be sited. The purpose of proper location of wells is to achieve the most efficient and sustainable energy production.

Figures 3.5 describes the results of reservoir pressure from simulation.

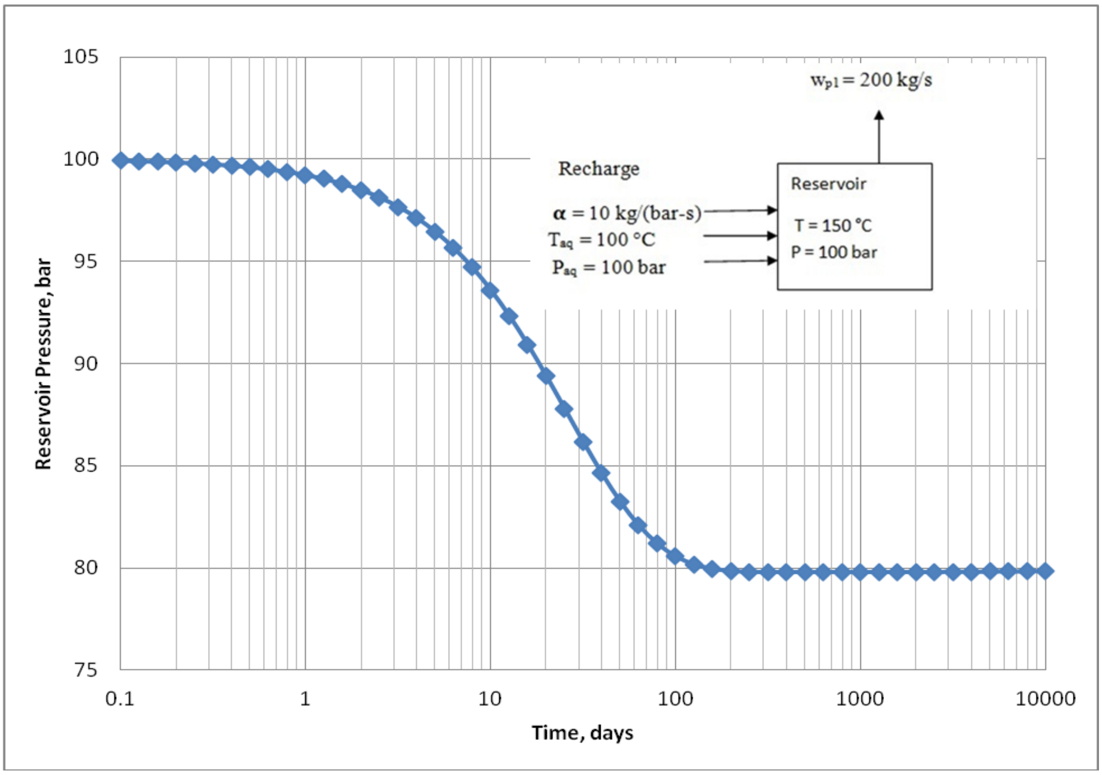

Figure 3.5 : Pressure behaviour for 1 tank – 1 recharge source for 10,000 days.

After a steep decline in reservoir pressure from onset of production to 100 days, steady-state condition is reached at 80 bar. Steady state condition implies a balance between strong water influx from an infinite-sized aquifer and the constant rate of production.

Reservoir temperature remains at initial level of 150°C till the end of 100 days of production. Temperature decline does not stabilize throughout entire production time. Temperature declines to 138°C at the end of the chosen operation life as a result of influx of cooler recharge water from aquifer.

Figures 3.6 describes the results of reservoir temperature behaviour from simulation.

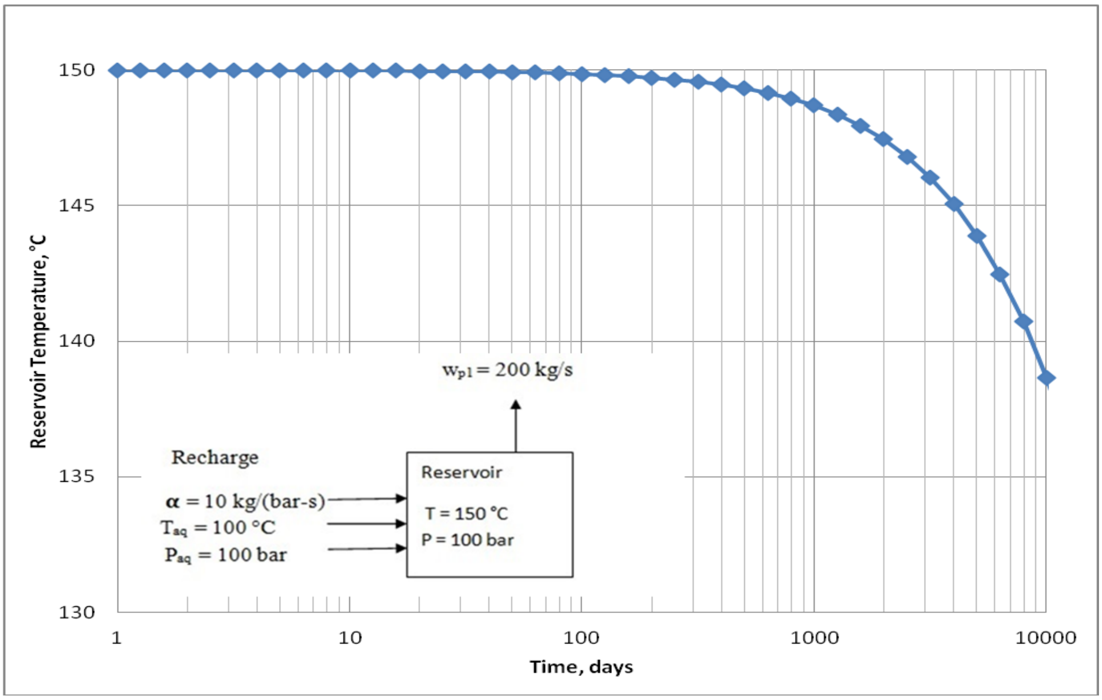

Figure 3.6 : Temperature behaviour for 1 tank – 1 recharge source for 10,000 days.

3.3.2. 2 tank – 1 recharge source model

Figure 3.7 shows the nature of this type of model describing two adjacent leases under competitive operation.

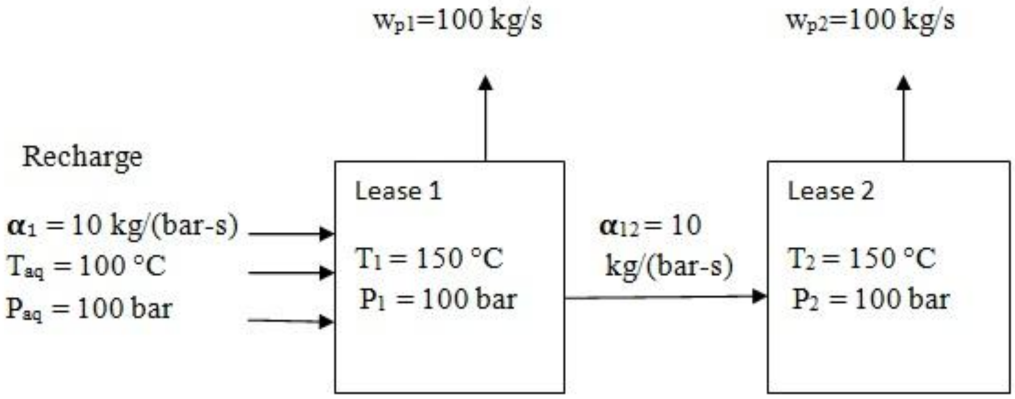

Figure 3.7 : Illustration of 2 tank – 1 recharge source model.

Location of wells is haphazard as lease owners drill wells from surface boundaries without sound engineering backing. The leases are therefore not developed in a balanced and efficient manner which brings about physical waste and under utilization of the geothermal resource. It is assumed that both leases are under equal rates of production at 100 kg/s. Results from simulation are presented in Figures 3.8 and 3.9.

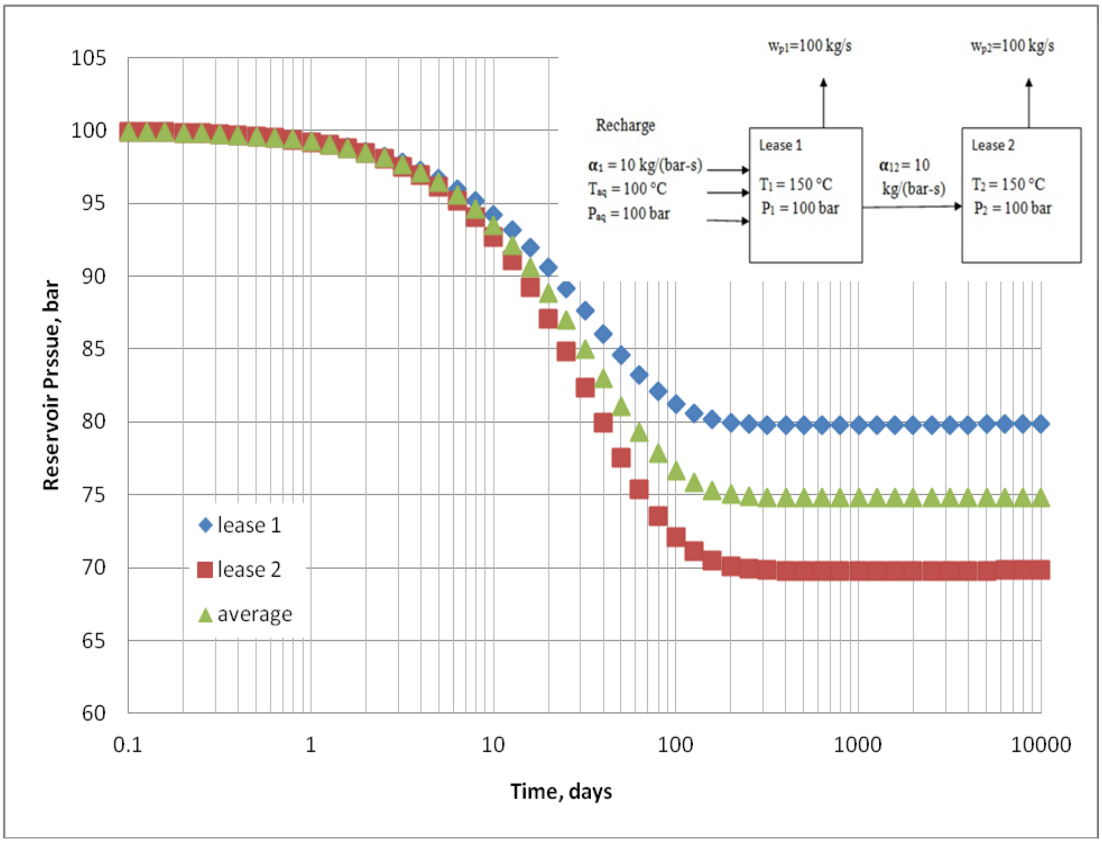

Figure 3.8 : Pressure behaviour for 2 tank – 1 recharge source for 10,000 days.

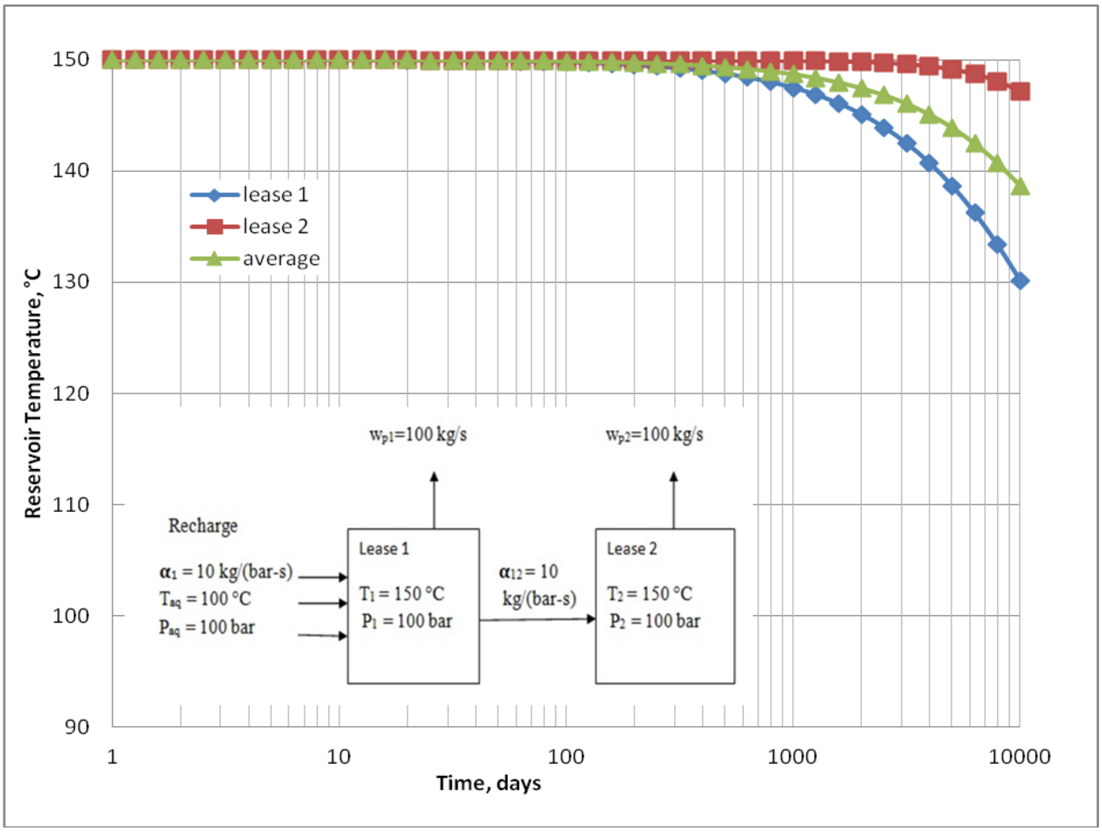

Figure 3.9 : Temperature behaviour for 2 tank – 1 recharge source for 10,000 days.

Pressure decline in Lease 2 is steeper than in Lease 1 because of added pressure drop effects from Lease 1. The inter-lease recharge constant has effect only on pressure drop in the lease 2.

Pressure decline in Lease 1 is relatively lower because it is directly linked to the infinite-size aquifer from which it benefits from a high inflow of recharge. Steady-state reservoir pressure is observed from10,000 days of production at 80 bar in Lease 1. However in the Lease 2, steady-state pressure is observed from the same time at a lower pressure value of 70 bar. Average reservoir pressure is at 75 bar by end of the design life.

Lease 2 has a lower rate of temperature decline for the chosen production period of 10,000 days. It has a temperature of 147.2°C compared to 130.2°C in Lease 1. This is because temperature in Lease 1 is affected by the colder recharge temperature but Lease 2 receives hot inter-lease recharge from the first tank in response to pressure drop. This situation benefits Lease 2 and provides higher energy content for utilization. Average reservoir temperature falls to 120.2°C after 10,000 days.

3.3.3. 2 tank – 2 recharge source model

The 2 tank – 2 recharge source model is represented by Figure 3.10.

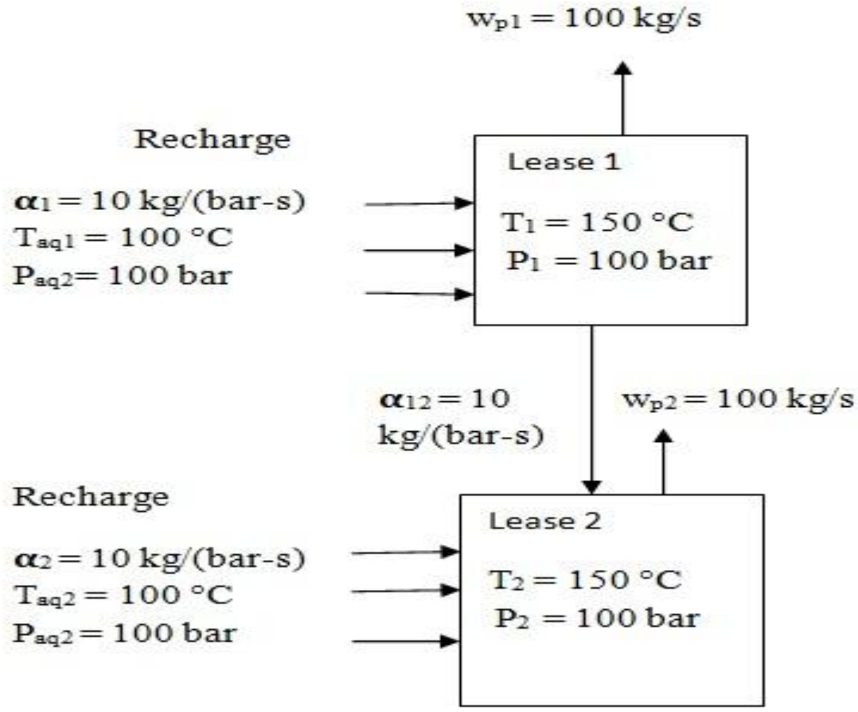

Figure 3.10 : Illustration of the 2 tank– 2 recharge source model.

Steady-state pressure drop equations for the two leases in this model are given respectively;

$$\Delta P_{ss1} = \frac{w_1(\alpha_2 + \alpha_{12}) + w_2\alpha_{12}}{\alpha_1\alpha_2 + \alpha_{12}(\alpha_1 + \alpha_2)} \tag{3.14}$$

$$\Delta P_{ss2} = \frac{w_2(\alpha_1 + \alpha_{12}) + w_1\alpha_{12}}{\alpha_1\alpha_2 + \alpha_{12}(\alpha_1 + \alpha_2)} \tag{3.15}$$

It is assumed that both leases are under equal rates of production at 100 kg/s.

Results from simulation are shown in Figures 3.11 and 3.12.

Pressure behaviour for both leases is the same because both are replenished by recharge sources and geothermal fluids are produced at the same rates.

In both cases, steady-state pressure conditions start from day 10,000 at 90 bar. This model has the least pressure drop compared to the previous tank models.

Similarly because both leases are supplied with colder water from separate recharge sources and production rates are equal, temperature behaviour is identical. At the end of project life, the reservoir temperature in the each lease decreases to 138.6 °C.

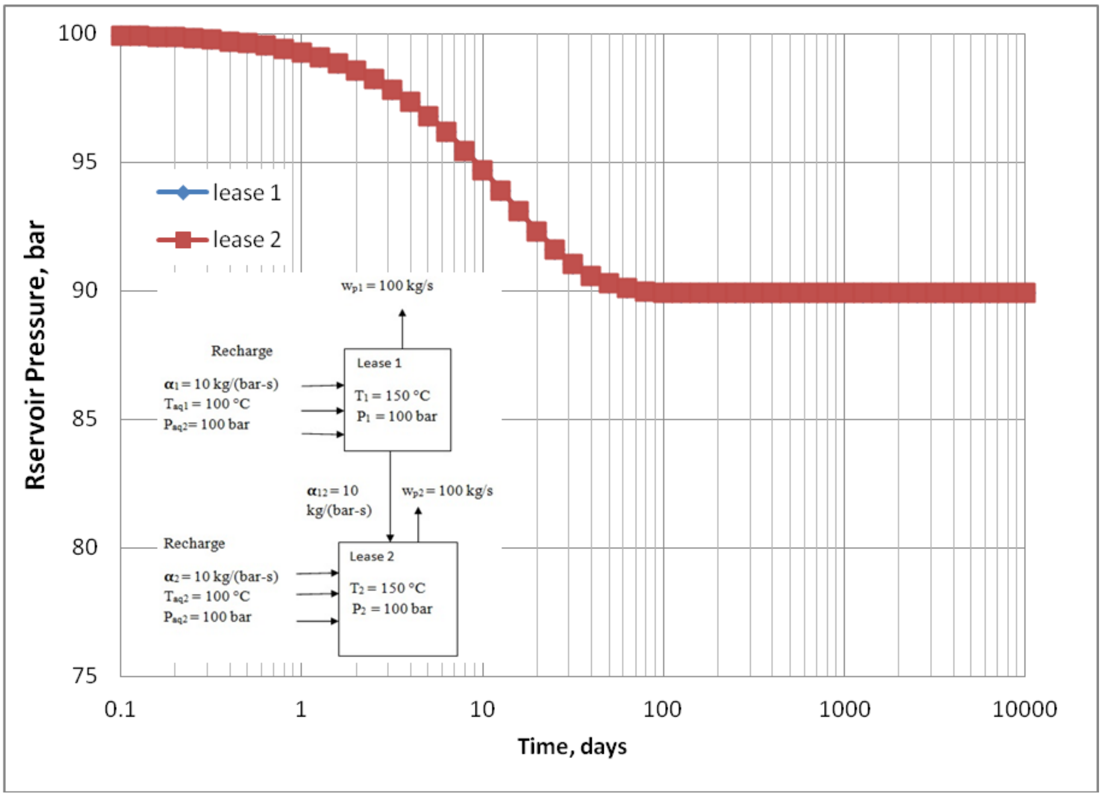

Figure 3.11 : Pressure behaviour for 2 tank – 2 recharge source for 10,000 days.

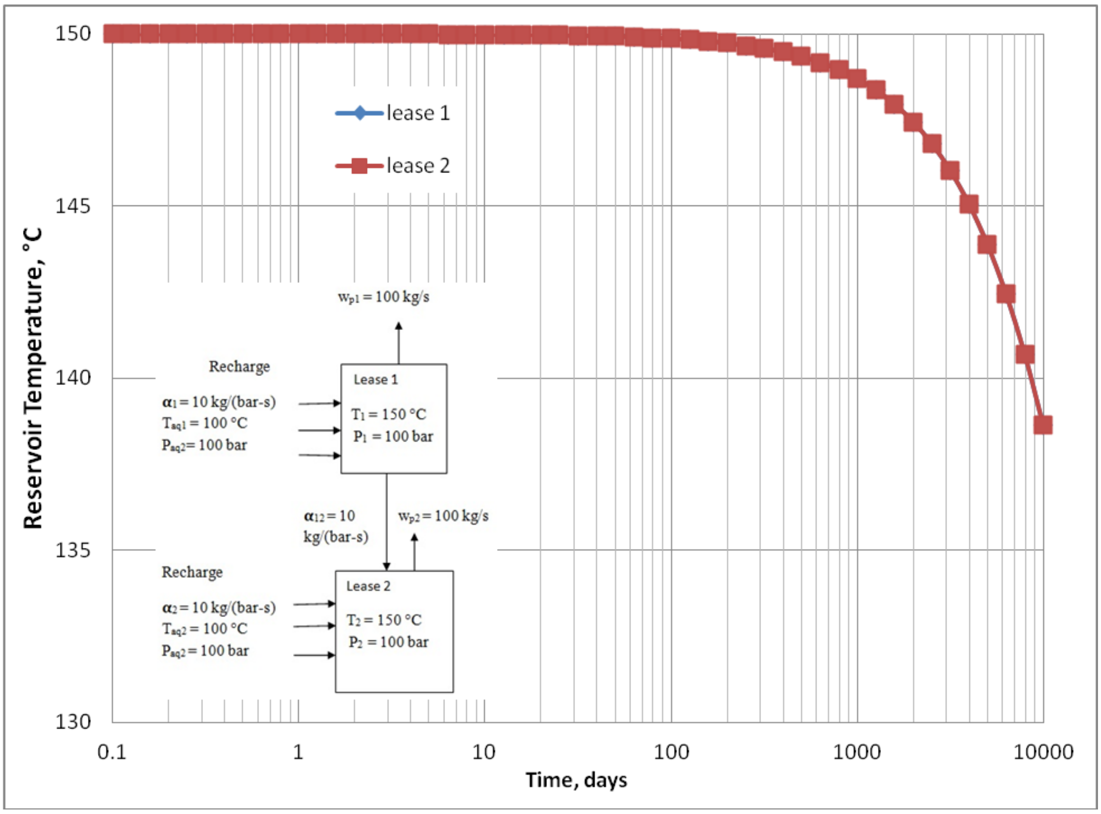

Figure 3.12 : Temperature behaviour for 2 tank – 2 recharge source for 10,000 days.

4. CONSTANT ELECTRICITY GENERATION CAPACITY

Three hypothetical scenarios of the one-tank and two-tank models will be proposed and analysed to study reservoir pressure and temperature behaviour relative to reservoir fluid production and time, with reinjection, under competitive and cooperative managements for constant electricity generation. The significance of this thesis is emphasized on selection of the most suitable development approach to execute this project for a reservoir shared by two straddled lease holders. As such, all the cases are evaluated on in terms of average reservoir pressure, average reservoir temperature, net produced heat, and thermal efficiency of the power plant. The assumptions made in this study are as follows;

1. Arbitrarily chosen reservoir rock and fluid properties in both leases.
2. Constant electricity generation from binary power plants.
3. A binary power plant with 10 MW_e electricity generation capacity is installed on each competitive geothermal lease of different reservoir temperatures; or a binary power plant with 20 MW_e electricity generation capacity is installed on the unitized leases.
4. Temperature of the recharge (aquifer) and its connected Lease 1 are equal at 180°C in all cases.
5. Reservoir temperature in Lease 2 is 160°C.
6. Project design life is limited to 10,000 days for all cases.

The assumed parameters representing reservoir fluid and rock properties are presented in Table 4.1. The evaluated cases are listed below:

1. Case 1: Competitive Approach with two leases
2. Case 2: Cooperative Approach with unitized two leases

3. Case 3: Cooperative Approach with unitized two leases (production in one lease and reinjection in other lease)

Table 4.1 : Rock and fluid properties of a hypothetical geothermal reservoir for reinjection considered.

	One-Tank Model	Two-Tank Model	
Parameter		Lease 1	Lease 2
Bulk volume of rock, m^3	1×10^9	0.5×10^9	0.5×10^9
Specific heat capacity of rock, J/(kg-°C)	1000	1000	1000
Rock compressibility, 1/bar	1×10^{-4}	1×10^{-4}	1×10^{-4}
Initial Pressure of reservoir, bar	150	150	150
Initial temperature of reservoir, °C	170 (Average of the two leases)	180	160
Porosity, fraction	0.15	0.15	0.15
Density of rock, kg/ m^3	2600	2600	2600
Recharge constant, kg/(bar-s)	$\alpha_1 = 5$	$\alpha_1 = 5$	$\alpha_{1,2} = 5$
Recharge temperature, °C	180	180	180

4.1. Binary Power Plants

Electricity is generated from geothermal energy by using steam or a working fluid (hydrocarbon vapour) to turn a turbine-generator set. Dry-steam geothermal resource can be used directly for this purpose. Hot-water resource however, needs to be flashed by reducing the pressure to produce steam, usually in the 15-20% interval. To improve efficiency, some plants are equipped with double or triple flash technologies. Low-temperature geothermal resources predominantly require the use of a secondary low-boiling point hydrocarbon to generate vapour to run the turbine in a binary power plant.

By the end of 2014, there were 613 operational geothermal power plants in the world (Bertani, 2015). Table 4.2 shows recorded installed capacities and share in total installed capacity of these power plants.

The flash plants are deployed in hot water reservoirs with temperature range above 180°C, where steam is separated from water to drive the turbine. The dry steam plants which are the oldest type of geothermal plants are operationalized in fields with temperature range between 180-225°C , where water or steam phase separation is not required.

The binary power plants are heat-operated cycles that convert heat from the geothermal fluid into electricity by transferring geofluid heat to a low-boiling point, organic working fluid like isopentane, kept in a closed circuit. Heating evolves out pressurised vapour from the working fluid, which expands through the turbine to produce shaft work required to drive the generator to produce electric power. Care should be taken to separate liquid carried over by the vaporised working fluid so the droplets do not fall on the turbine blades. Efficiency of this plant is reduced by heat losses, mainly due to heat input to the system which is limited by temperature difference since geofluid temperature cannot be cooled down to ambient conditions. Other irreversibilities arise from temperature and enthalpy differences between the geofluid and the working fluid, as well as electrical and mechanical losses which reduce the ultimate generated net output.

Table 4.2 : Installed capacities and share in total installed capacity of geothermal power plants (Bertani, 2015).

Type	Number	Installed Capacity for Each Type, (MW_e)	Share in Total Installed Capacity, (%)
Flash	237	7805	62
Binary	286	1790	12
Dry Steam	63	2863	22
Hybrid	1	2	1
Back-pressure	26	181	3
Total	613	12,640	100

Binary power plants are a well-established technology for utilizing low- to moderate-temperature geothermal fluids (DiPippo, 2004; DiPippo, 2005). It is employed for reservoirs with temperature range between 100-180°C. Examples of installed binary power plants in operation are the Salavatli- Aydin and Tuzla-Çanakkale power plants in Turkey, Svartsengi power plant in Iceland, and the Bacman-I power plant in the Philippines. Figure 4.1 shows the schematic of a binary power plant.

Binary power plant is becoming a popular choice in the modern geothermal electricity market. These plants enable power generation from low-temperature geothermal resources, previously impossible in the past. Binary plants on the reinjection stream is a potential for generating economical energy, because there would not be any additional pumping costs (World Energy Resources, 2013).

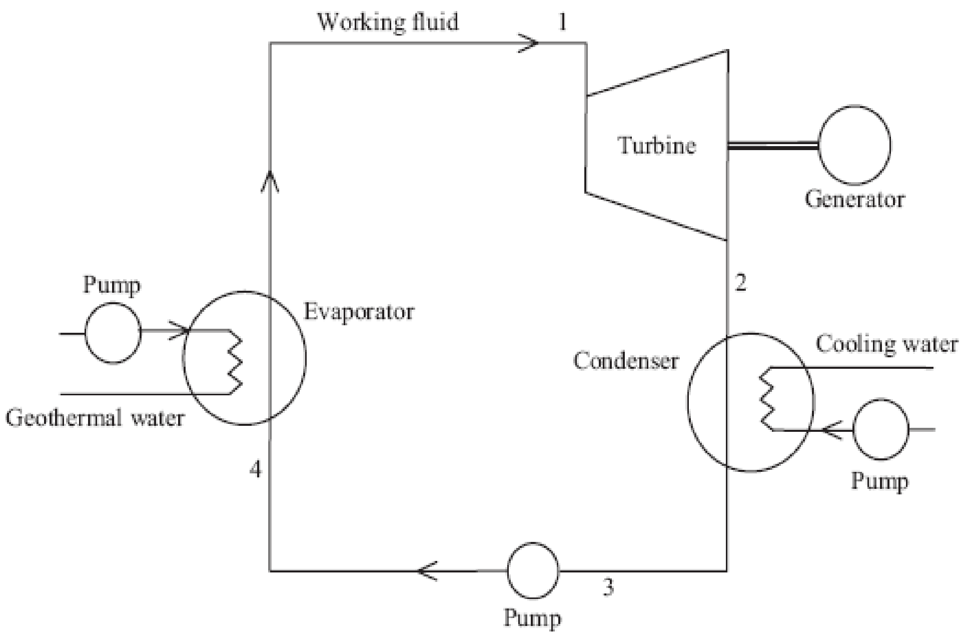

Figure 4.1 : Schematic of a basic binary power plant.

4.2. Thermal Efficiency

Thermal efficiency can be defined as the percentage of heat that can be converted to electricity, i.e., the fraction of the total heat delivered to the power cycle by the circulating geofluid that is converted to electrical energy (MIT, 2006).

Thermal efficiency of the binary plant is calculated using a correlation derived from cycle thermal efficiencies for several binary power plants, as shown in Figure 4.2.

$$\eta_{th} = 0.0935\mathrm{T} - 2.3266 \qquad (4.1)$$

where;

η_{th} Thermal efficiency, %

T Geofluid temperature, °C

Determining thermal efficiency, production and reinjection rates for reservoir temperature of 180 °C : In all cases, temperature drop as a result of heat losses as geofluid is conducted up the wellbore is assumed to be 10 °C.

At reservoir temperature, T_r equal to 180 °C, the actual inlet temperature of the geofluid entering the heat exchanger, T_1 is therefore 170 °C and the thermal efficiency given by;

$$\eta_{th} = (0.0935 \times 170) - 2.3266 = 13.6\% = 0.136$$

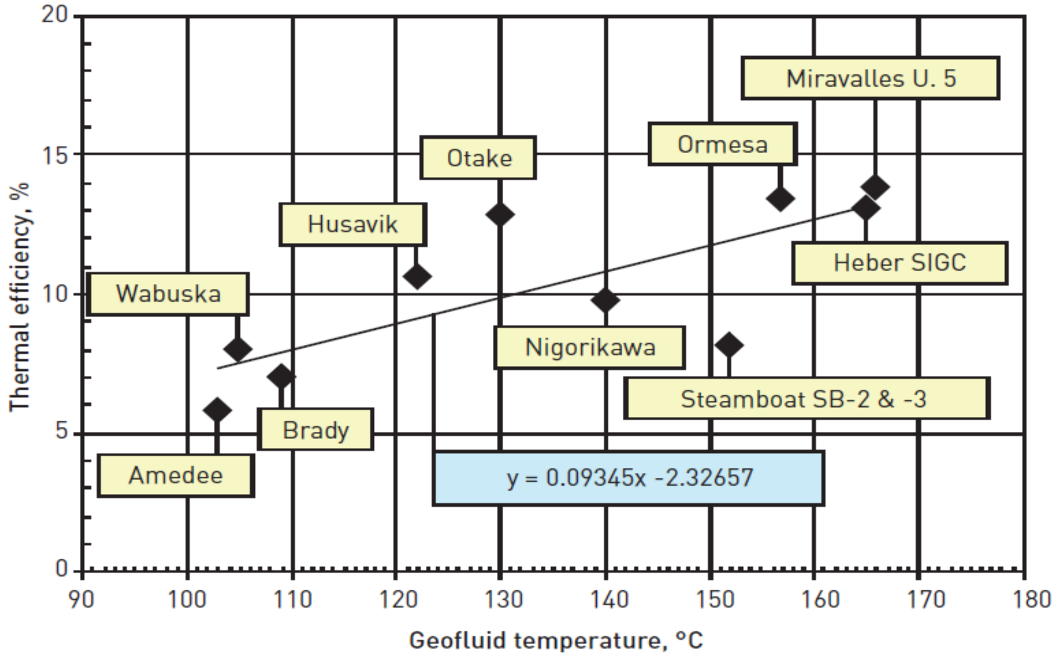

Figure 4.2 : Cycle thermal efficiencies for several binary power plants (MIT, 2006).

Thermal power output from geofluid;

$$\eta_{th} = \frac{Q_{out}}{Q_{in}} \tag{4.2}$$

where;

Q_{out} Thermal power output

Q_{in} Thermal power input; given as 10 MW_e=10,000 kJ/s

$$Q_{in} = \frac{Q_{out}}{\eta_{th}} = \frac{10{,}000\, kJ/s}{0.136} = 73{,}529\, kJ/s$$

To estimate geofluid flow rate, graph of Specific Power Output (S.P.O), vs Geofluid Temperature shown in Figure 4.3 is employed.

T_2 which is the exiting temperature of the working fluid from the turbine, is chosen as 35°C in all cases. Reinjection temperature T_{ri} is selected at 85°C to avoid scaling problems on the heat exchanger and in the reinjection wells. Scaling can drastically reduce well productivity and electricity generation output especially in carbonate geothermal formations like limestone and marble. T_{ri} should also be chosen below saturation point of water to prevent two phase flow of geofluid which can impair the reinjection pump through cavitation effects near the surface of the device.

The enormous quantities of wastewater generated can be reinjected into the formation and also recycled for useful purposes.

For our demonstration purpose, 80% of produced reservoir fluid is assumed to be reinjected into the reservoir.

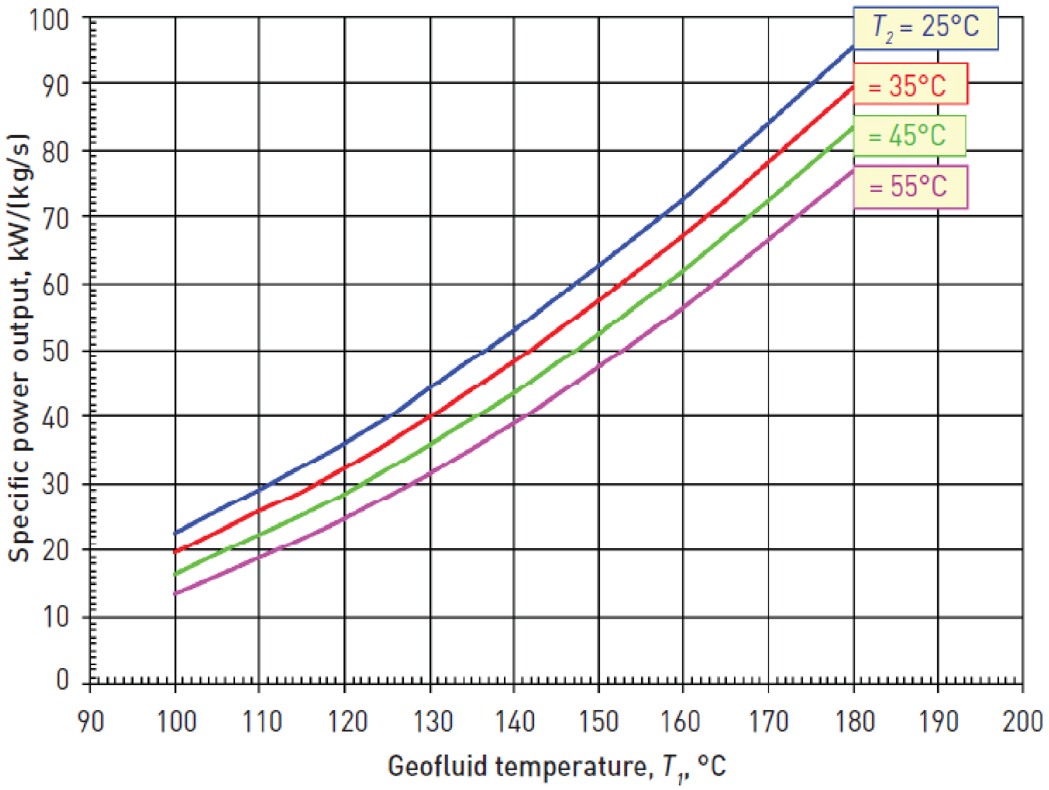

Figure 4.3 : Specific power output [in kW/(kg/s)] for low-to moderate- temperature geofluids as a function of inlet (T_1) and Outlet (T_2) temperatures shown in °C (MIT, 2006).

At a geofluid temperature flowing through the heat exchanger, T_1 being equal to 170 °C, exiting working fluid temperature, T_2 equal to 35°C, specific power output is read from Figure 4.3 as 78 [kW/(kg/s].

$$w = \frac{1}{S.P.O} \times Q_{out} = \frac{1}{78[kJ/s/(kg/s)]} \times 10{,}000\,kJ/s = 128\,kg/s$$

Reinjection; $w_{ri} = 128\,kg/s \times 0.8 = 102\,kg/s$

Determining thermal efficiency, production and reinjection rates for reservoir temperature of 160 °C : At reservoir temperature, T_r equal to 160 °C, the actual inlet temperature of the geofluid entering the heat exchanger, T_1 is 150 °C.

$$\eta_{th} = (0.0935 \times 150) - 2.3266 = 11.7\% = 0.117$$

$$\mathrm{Q}_{in} = \frac{\mathrm{Q}_{out}}{\eta_{th}} = \frac{10{,}000\,kJ/s}{0.117} = 85{,}470\,kJ/s$$

At T_1 = 150 °C , T_2 = 35 °C, specific power output = 57 [kW/(kg/s)]

$$w = \frac{1}{S.P.O} \times \mathrm{Q}_{out} = \frac{1}{57\left[kJ/s/(kg/s)\right]} \times 10{,}000\,kJ/s = 175\,kg/s$$

Reinjection; $w_{ri} = 175\,kg/s \times 0.8 = 140\,kg/s$

Natural recharge though a compensatory phenomenon for reservoirs is not sufficient enough to replace the large mass of produced reservoir fluids for direct or electric power usages. Reinjection of produced geothermal fluid is a measure which has physical, economical, and environmental benefits. Channelling produced water back to the reservoir is a valuable pressure maintenance technique which increases average drainage pressure to support sustainable production rates. Since most of the trapped energy in a geothermal reservoir resides in the rock volume, pumping of cold water is an economic way of extracting this vast energy for commercial exploitation. By reinjecting produced water into formations, freshwater bodies are and for that matter aquatic life, and access to potable water are protected.

However reinjection of colder water relative to reservoir conditions creates a temperature differential which ultimately reduces the reservoir temperature.

Make-up well drilling compensates for decline in well productivity as a result of reservoir pressure depletion and deposition, which may occur within the formation around the wells, further reducing well productivity. These additional wells are drilled to replenish the reduced steam delivery.

4.3. Case 1: Competitive Approach with Two Leases

Figure 4.4 describes a reservoir being developed in two adjacent leases under competitive operation.

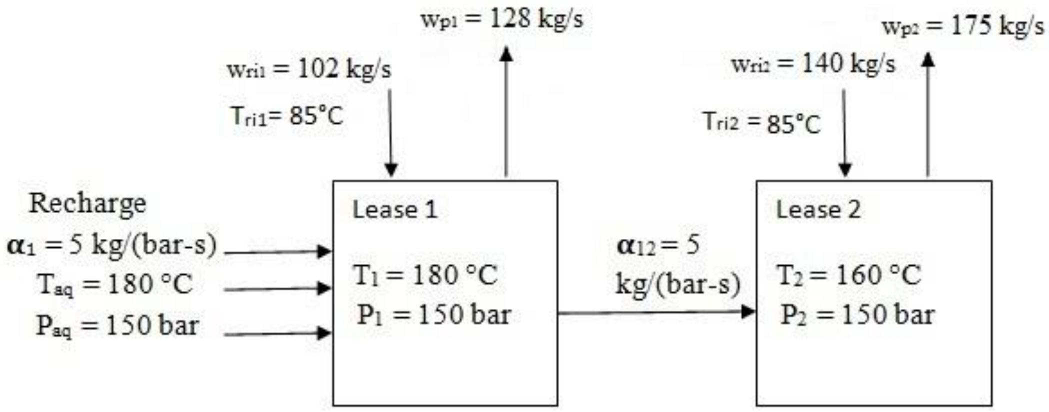

Figure 4.4 : Illustration of competitive approach with two leases.

The production and reinjection rates are fed into the simulator to regenerate reservoir pressure and temperature behaviour over the design life of 10,000 days as shown in Figures 4.5 and 4.6.

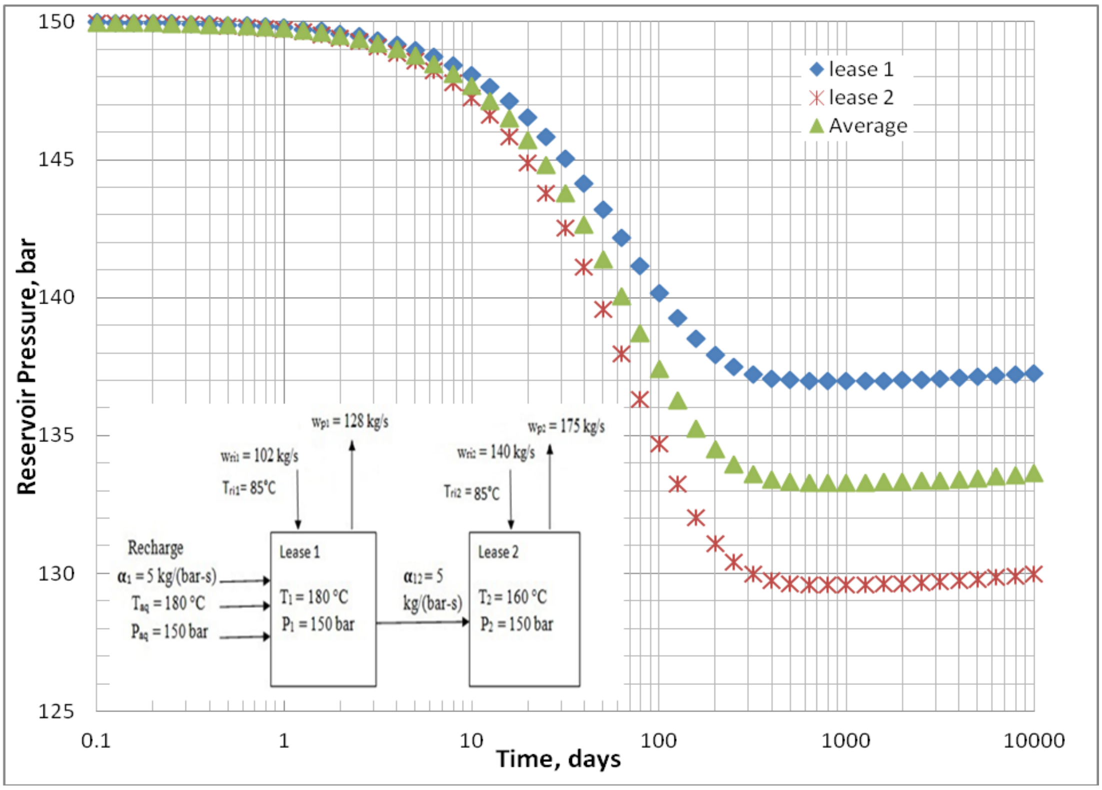

Figure 4.5 : Behaviour of reservoir pressure vs time; competitive case with two leases.

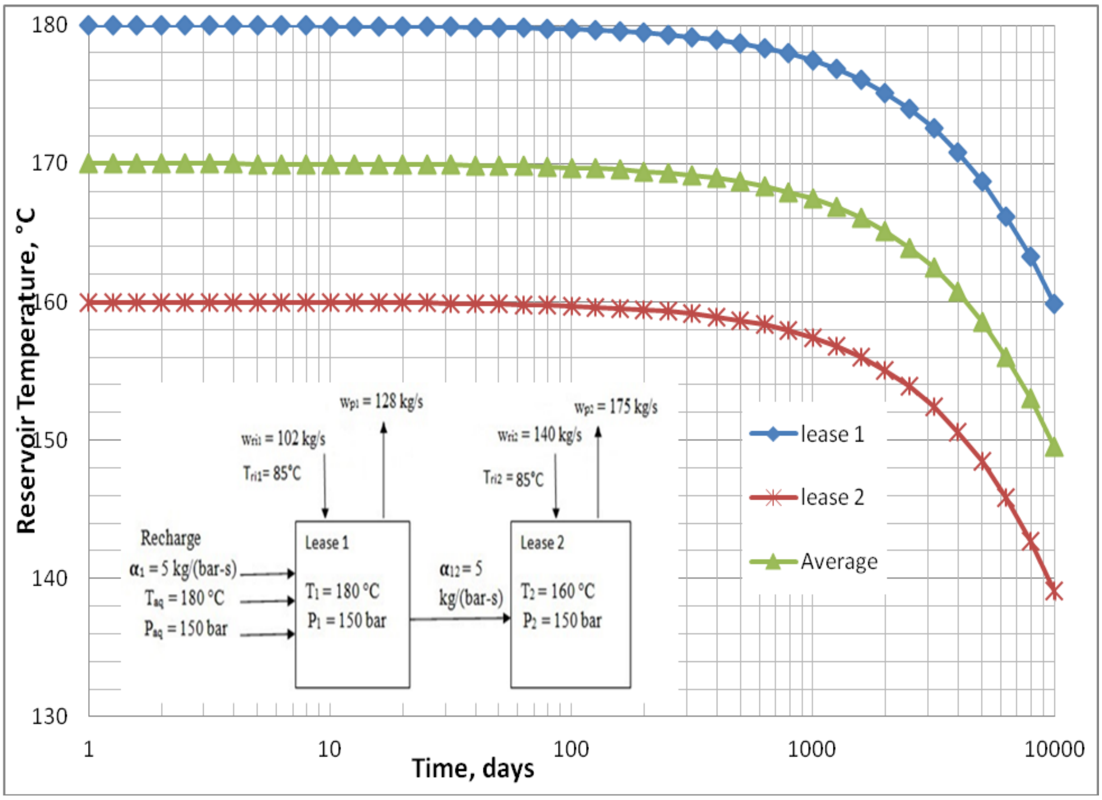

Figure 4.6 : Behaviour of reservoir temperature vs time; competitive case with two leases.

In the Lease 1, pressure decreases to 137 bar in 1000 days because rate of replenishment into Lease 1 by natural recharge and reinjection is insufficient to balance production rate. Pressure increases marginally to 137.3 bar in 10,000 days as pressure maintenance improves, and finally stabilizes at 137.8 bar as a result of equilibrium between rates of production and recharge.

Unlike Lease 1 which drains directly from an infinite-size recharge source in response to pressure drop, water influx from Lease 1 into Lease 2 is dictated by pressure difference between the two leases.

Reservoir pressure declines relatively lower in Lease 2 to 130 bar by the end of project life due to interference effects from Lease 1. Again, the lower the pressure drop in Lease 2, the lower the time rate of recharge from Lease 1 into Lease 2. For a quicker time rate of influx from Lease 1, there must be a high pressure drop in Lease 2.

Reinjection is a helpful pressure maintenance mechanism which helps to shore up reservoir pressure in both leases and also increases steady state pressure . Difference in recharge rates ensure that steady state pressures in both leases vary. Average reservoir pressure decreases to 133.6 bar by end of project life.

Equations 3.5 and 3.6, are used to calculate for steady-state pressure drops of the two leases respectively.

$$\Delta P_{ss1} = \frac{w_{pn1} + w_{pn2}}{\alpha_1} = \frac{26+35}{5} = 12.2\,bar$$

$$P_{ss1} = P_i - \Delta P_{ss1} = 150 - 12.2 = 137.8\,bar$$

$$\Delta P_{ss2} = \Delta P_{ss1} + \frac{w_{pn2}}{\alpha_{12}} = 12.2 + \frac{35}{5} = 19.2\,bar$$

$$P_{ss2} = P_i - \Delta P_{ss2} = 150 - 19.2 = 130.8\,bar$$

The volumetric average steady-state reservoir pressure loss $\left(\overline{\Delta P_{SS}}\right)$ is given by;

$$\overline{\Delta P_{ss}} = \frac{\left(V_{p1}\Delta P_{ss1}\right) + \left(\left(V_{p2}\Delta P_{ss2}\right)\right)}{V_{p1} + V_{p2}} = \frac{\left(0.5\times10^9 \times 12.2\right) + \left(0.5\times10^9 \times 19.2\right)}{1\times10^9} = 15.7\,bar$$

$$\overline{P}_{SS} = P_i - \overline{\Delta P} = 150 - 15.7 = 134.3\,bar$$

Reservoir temperature drops in both leases mainly because of reinjection at a low temperature of 85 °C, as shown in Figure 4.6. Temperature decline in Lease 1 by the end of design life is 159.9 °C.

Owing to lower reservoir temperature in Lease 2, higher rate of hot liquid production is required to generate the same plant capacity of 10 MW_e, and therefore higher withdrawal of heat from reservoir. Reservoir temperature falls to 139.1°C after 10,000 days in Lease 2. Average reservoir temperature drops to 149.5°C by end of project life.

Analytical expression derived by Satman (2010) for case of production, reinjection, and recharge, is applied to determine average reservoir temperature at 10,000 days which considers the geothermal system to be in thermodynamic equilibrium . Since this expression was developed for one tank lumped parameter model, in the case of competitive production, average reservoir temperature $\left(\overline{T}\right)$ is computed as if the leases were a single tank;

$$\overline{T} = T_i e^{-at} + \frac{b'}{a}\left[1 + \frac{D}{a-D}e^{-at} - \frac{a}{a-D}e^{-Dt}\right] - \left(\frac{g}{a}\right)\left(e^{-at} - 1\right) \quad (4.3)$$

where:

D, a, b', g are parameters defined in Table 4.3.

This derivation assumes constant specific heat capacity value at surface conditions for production, recharge, and reinjection.

Computation of the various constants and the average temperature in 10,000 days is given in Table 4.3.

Table 4.3 : Values of computed parameters for Case 1.

Parameter	Values
Initial reservoir temperature, °C	170
$\kappa = V\phi \rho_w C_t$, kg/bar	1.35×10^{7}
$D = \frac{\alpha}{\kappa}$, 1/s	3.71×10^{-7}
$\rho_{av} C_{av}$, kJ/m^3	2775
$a = \frac{w_p C_{pw}}{V \rho_{av} C_{av}}$, 1/s	4.59×10^{-10}
$b' = \frac{w_{pn} C_{pwr} T_r}{V \rho_{av} C_{av}}$, 1/s	1.66×10^{-8}
$g = \frac{w_{ri} C_{pwri} T_{ri}}{V \rho_{av} C_{av}}$, 1/s	3.11×10^{-8}
Average reservoir temperature, $\overline{T}$, °C	148

Slight differences in average temperature values arise between the simulator and analytical average temperature values . This is because the analytical expression was derived for single tank lumped parameter model under the assumptions of constant specific heat capacity value at surface conditions for production, recharge, and reinjection for a geothermal reservoir containing fluid which exists as a compressed liquid. The derivation also assumes a balance between heat in and heat out due to conduction for the production case. This variation is shown in Table 4.4 and Figure 4.7.

The net heat produced after 10,000 days can also be determined analytically using Equation 4.4. Total production time is divided into equal time intervals while using average reservoir temperature for each time interval.

$$Net\ Heat\ \mathrm{Pr}oduced = \sum_{i=1}^{n}\left(w_{pi}\times\overline{T}_i\times C_p\right)\times\Delta t - \sum_{i=1}^{n}\left(w_{ri}\times T_{ri}\times C_p\right)\times\Delta t \tag{4.4}$$

where;

i: 1,2,3,...,n are time intervals

$\overline{T}_i$ is the average reservoir temperature of the time interval

C_p is the thermal heat capacity

Δt is the time period

Hence, $Net\ Heat\ \mathrm{Pr}oduced = 1.66\times10^{17}\ J$

Table 4.4 : Comparison of average reservoir temperature values obtained from simulator and analytical calculations in Case 1.

	Simulator	Analytical
Time, days	Average Reservoir Temperature, °C	Average Reservoir Temperature, °C
0	170	170
1000	167.5	167
2000	165.1	165
3000	162.5	163
4000	160.7	160
5000	158.6	158
6000	156	156
7000	154	154
8000	153	152
9000	151	150
10000	149.5	148

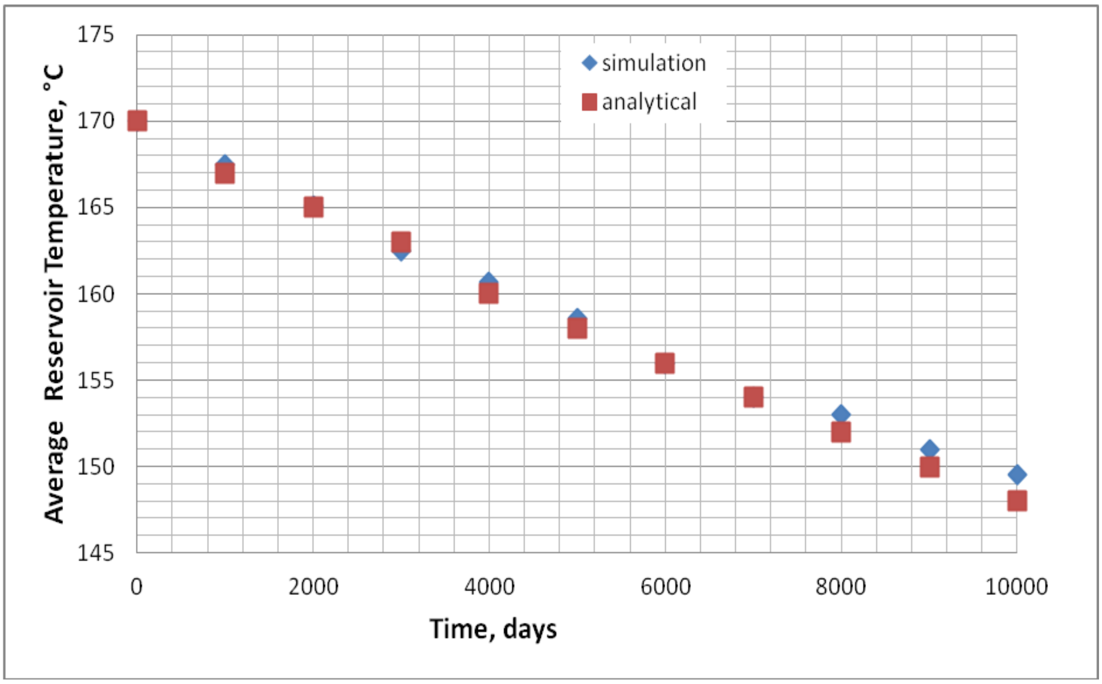

Figure 4.7 : Comparison of simulator and analytical average reservoir temperature values; competitive case with two leases.

For constant generation of stated capacity : Production of geofluid causes decline in reservoir pressure and reservoir temperature. Net heat produced from withdrawal of geofluid drives the binary power plant to generate electricity. Decrease in reservoir temperature with time as production continues means lower net heat produced from the reservoir with subsequent fall in electricity generation capacity. Therefore in order to run the power plant to generate a fixed output of 20 MW_e from the two leases, a constant power output is necessary.

There is the need to vary production rate of geofluid to match generation capacity. This is done by operating the plant at specified times to monitor drop in temperature, and adjusting geofluid production rate, in order to withdraw constant heat.

$$Q = wC_p \Delta T \tag{4.5}$$

For constant Q and C_{pw}, Equation 4.5 reduces to;

$$w_1 \Delta T_1 = w_2 \Delta T_2 = w_i \Delta T_i = \ldots i = 1, 2, 3, \ldots \tag{4.6}$$

The simulator is run at time intervals of 1000 days to monitor pressure and temperature drops in order to modify production rates to yield constant heat withdrawal. Results of variation in production rates and thermal efficiency of the binary power plant are shown in Table 4.5 and Figures 4.8 and 4.9.

Production rates increase with time as reservoir temperature falls. Example calculation after 1000 days for Lease 1 is shown;

$$128\,kg/s \times 180\,°C = w_{p1}(1000\,days) \times 177.5\,°C$$

$$w_{p1}(1000\,days) = \frac{128\,kg/s \times 180\,°C}{177.5\,°C} = 130\,kg/s$$

At average temperature of the reservoir, T_r being equal to 177.5 °C in Lease 1 and inlet geofluid temperature, T_1 as 167.5 °C by 1000 days, thermal efficiency of the binary power plant decreases to;

$$\eta_{th} = (0.0935 \times 167.5) - 2.3266 = 13.3\%$$

$$\Delta\eta_{th} = \eta_{th}(0\,day) - \eta_{th}(1000\,days) = 13.7 - 13.3 = 0.4\%$$

Table 4.5 : Results of varying production rates and thermal efficiencies for competitive operation with two leases.

	Lease 1				Lease 2			
Time, day	w_p, kg/s	w_{ri}, kg/s	Thermal Efficiency of binary plant, %	Change in Thermal Efficiency, $\Delta\eta_{th}$	w_p, kg/s	w_{ri}, kg/s	Thermal Efficiency of binary plant, %	Change in Thermal Efficiency, $\Delta\eta_{th}$
1000	128	102	13.3	0.3	175	140	11.7	0.2
2000	130	103	13.2	0.4	177	142	11.5	0.4
3000	133	106	12.9	0.7	182	146	11.3	0.6
4000	135	108	12.7	0.9	186	148	11.1	0.8
5000	136	109	12.5	1.1	188	150	10.9	1
6000	138	110	12.3	1.3	191	153	10.7	1.2
7000	140	112	12.1	1.5	194	155	10.5	1.5
8000	142	114	11.9	1.7	197	158	10.1	1.6
9000	143	114	11.8	1.8	200	160	9.9	1.8
10000	145	116	11.6	2.0	202	162	9.7	2.0

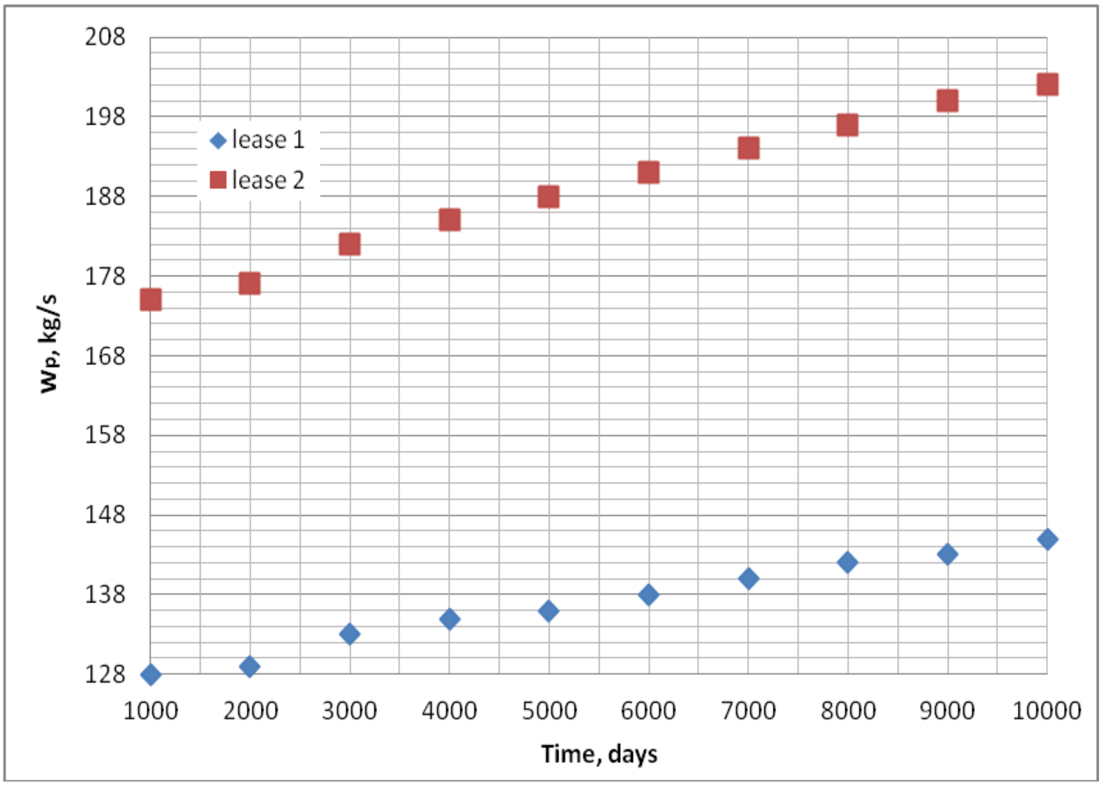

Figure 4.8 : Variation in production rate with time, competitive case with two leases.

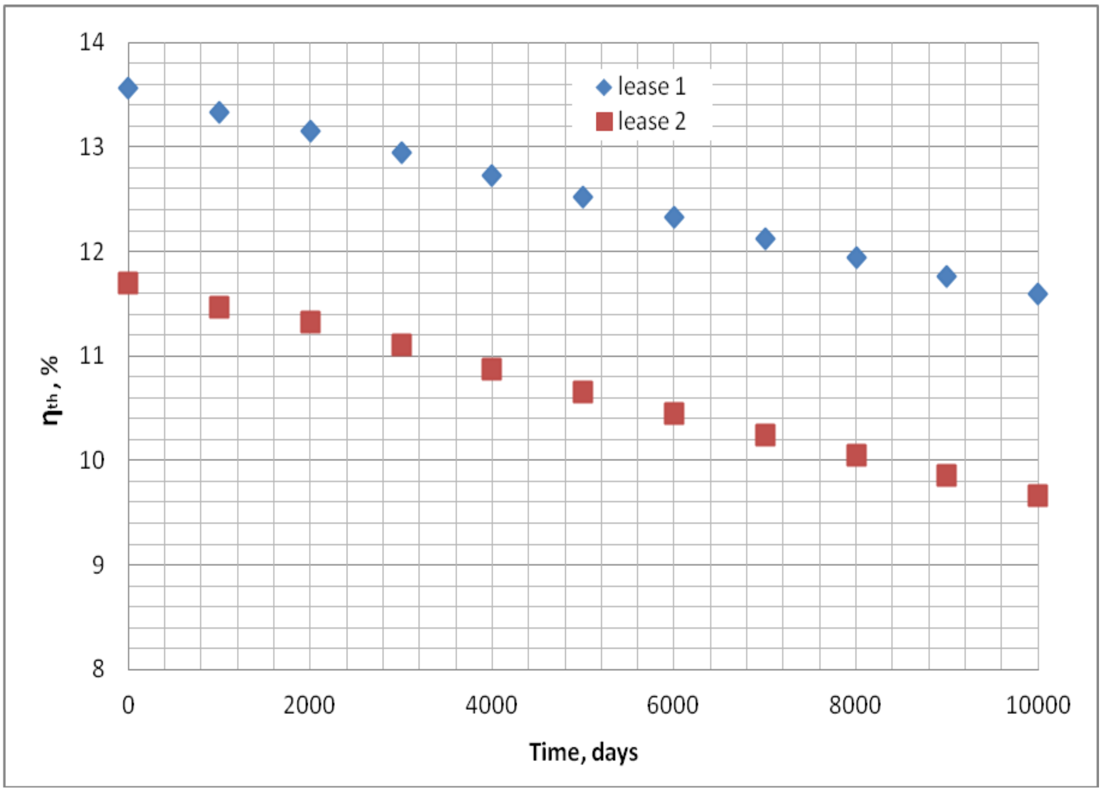

Figure 4.9 : Change in thermal efficiency versus time, competitive case with two leases.

Therefore it clearly shows that increment in production rates to commensurate with decrease in reservoir temperature decreases thermal efficiency of the binary power plant. It is clearly erroneous to assume constant geofluid production rate to meet a fixed power plant capacity.

There is 14.7% reduction in efficiency of the binary power plant in Lease 1 whereas in Lease 2 the efficiency of the binary power plant drops by 17.1% under competitive development scheme.

Constant generation of 20 MW_e from the two leases which brings about changes in production and reinjection rates, also yields slight differences in average reservoir temperature and average reservoir pressure values as shown in Table 4.6 and Figures 4.10 and 4.11.

From Equation 4.4, actual net heat produced for the constant electricity generation is $1.06 \times 10^{17}\ J$.

Table 4.6 : Comparison of average reservoir temperatures and average reservoir pressures for constant and varying production rates.

	Constant w_p and w_{ri}		Varying w_p and w_{ri}	
Time, day	Average Reservoir Temperature, °C	Average Reservoir Pressure, bar	Average Reservoir Temperature, °C	Average Reservoir Pressure, bar
0	170	150	170	150
1000	167.5	133.3	167.5	133.3
2000	165.1	133.3	165.6	133.5
3000	162.5	133.3	163.4	133.5
4000	160.7	133.4	161.1	132.9
5000	158.6	133.5	158.9	132.6
6000	156	133.5	156.7	132.3
7000	154	133.5	15436	132.4
8000	153	133.6	152.5	131.9
9000	151	133.6	150.5	131.4
10000	149.5	133.6	148.6	131.7

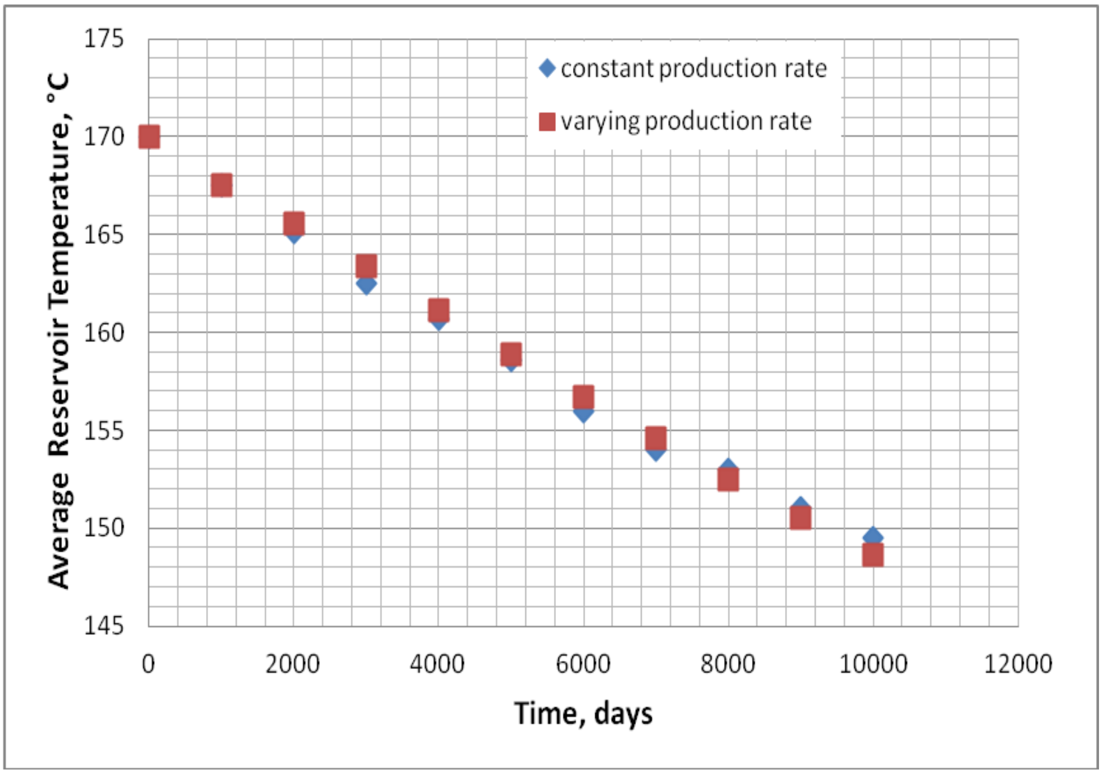

Figure 4.10 : Comparison of average reservoir temperatures for constant and varying production rates.

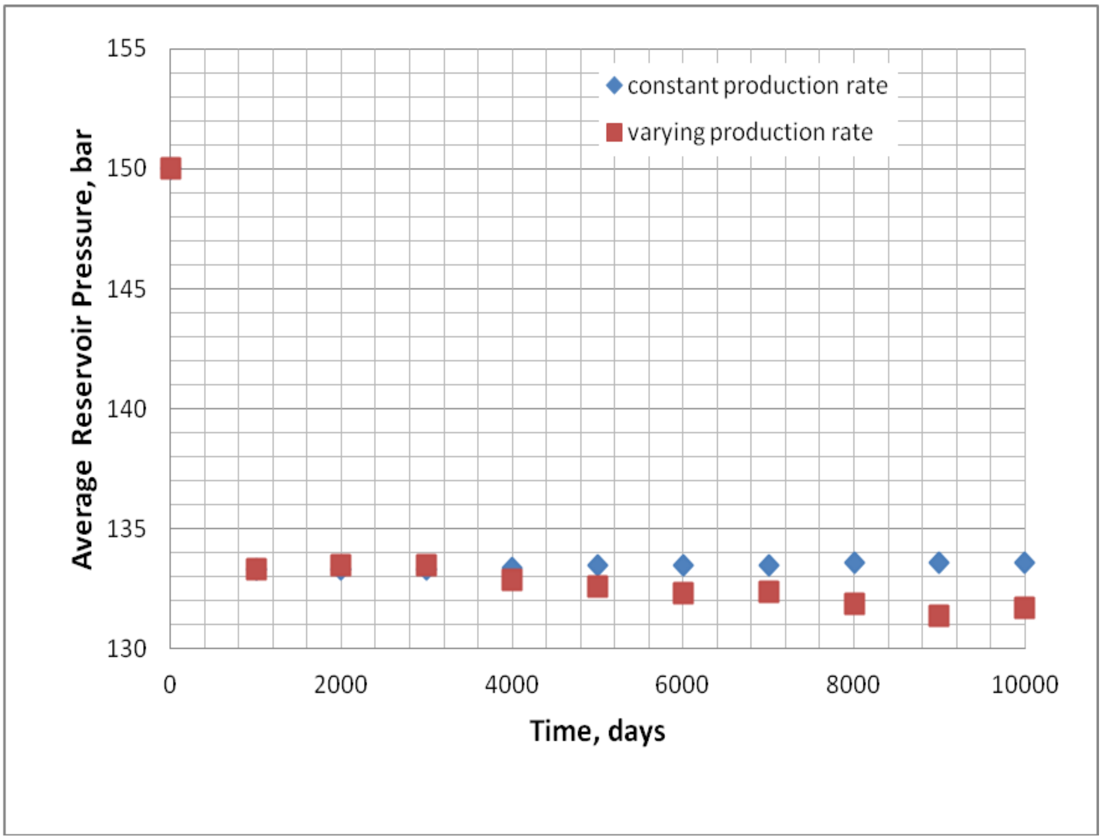

Figure 4.11 : Comparison of average reservoir pressures for constant and varying production rates, competitive case with two leases.

4.4. Case 2: Cooperative Approach with unitized two leases

Figure 4.12 decsribes the schematic of production and reinjection in a unitized case with one reservoir.

The reservoir is treated as a single tank from which injecion and reinjection are carried out.

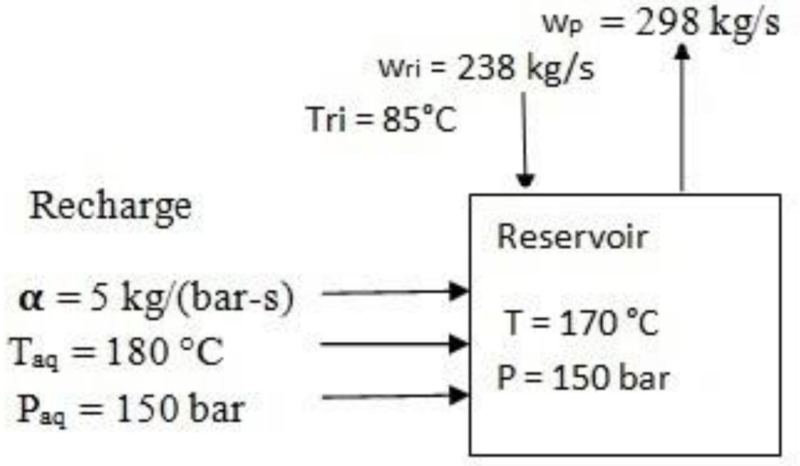

Figure 4.12 : Illustration of cooperative case with unitized two leases.

For the unitized approach (one-tank model), the volumetric average temperature of the two leases is used;

$$T_{avg} = \frac{(T_1 \times V_1) + ((T_2 \times V_2))}{V_t} = \frac{(180 \times 0.5 \times 10^9) + (160 \times 0.5 \times 10^9)}{1 \times 10^9} = 170\,°C$$

Determining thermal efficiency, production and reinjection rates for reservoir temperature of 170 °C : At a geofluid temperature flowing through the heat exchanger, T_1 being equal to 160 °C, exiting working fluid temperature, T_2 equal to 35°C, specific power output is read from Figure 4.4 as 67 [kW/(kg/s)].

$$\eta_{th} = (0.0935 \times 160) - 2.3266 = 12.6\% = 0.126$$

$$Q_{in} = \frac{Q_{out}}{\eta_{th}} = \frac{10{,}000\, kJ/s}{0.126} = 79{,}365\ kJ/s$$

$$w = \frac{1}{S.P.O} \times Q_{out} = \frac{1}{67[kJ/s/(kg/s)]} \times 10{,}000\, kJ/s = 149\, kg/s$$

For the two power plants (20 MW_e); $w = 149\,kg/s \times 2 = 298\,kg/s$

Reinjection; $w_{ri} = 298\,kg/s \times 0.8 = 238\,kg/s$

Pressure profile of this scenario from simulation is given in Figure 4.13.

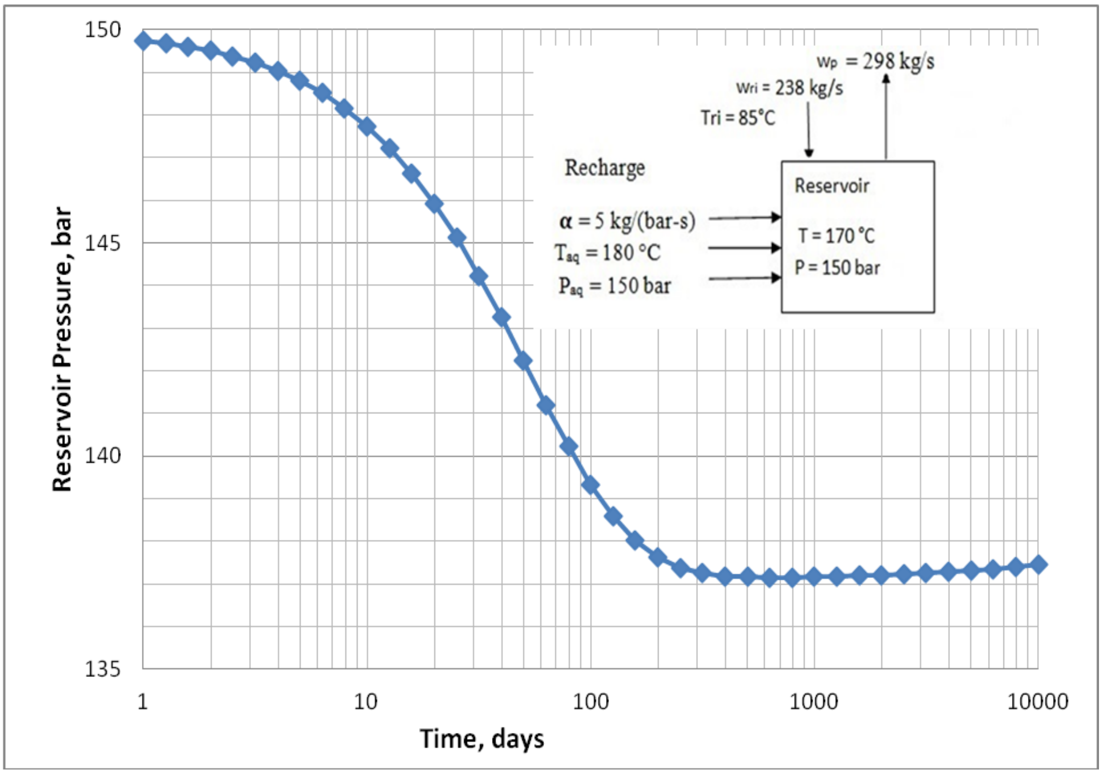

Figure 4.13 : Behaviour of reservoir pressure vs time; cooperative case with unitized two leases.

Decrease in reservoir pressure is lesser in Case 2, compared to the competitive case. This is because there is no additional pressure drop from another lease since both leases have been merged as a single field. Decrease in pressure is stabilized with refill from the infinite-size recharge source and reinjection at steady-state. There is extra pressure support given by reinjected water , which leads to a decrease in steady state pressure loss. By the end of design life, pressure drops to 137.5 bar.

This mode of unitization is well coordinated due to appropriate placement of wells to maximize heat withdrawal coupled with adequate reservoir pressure maintenance.

The 1-tank model of unitization is strongly preferred at the onset of reservoir exploitation.

The steady-state pressure loss for the reservoir is determined from Equation 1.5.

$$\Delta P_{ss} = \frac{w_{pn.}}{\alpha_{.1}} = \frac{60}{5} = 12\,bar$$

$$P_{ss} = P_i - \Delta P_{ss} = 150 - 12 = 138\,bar$$

The volumetric average steady-state reservoir pressure loss;

$$\overline{\Delta P_{ss}} = \frac{(V_p \Delta P_{ss})}{V_{p1} + V_{p2}} = \frac{(1 \times 10^9 \times 12)}{1 \times 10^9} = 12\,bar$$

$$\overline{P}_{ss} = P_i - \overline{\Delta P} = 150 - 12 = 138\,bar$$

Temperature drop arises from low temperature of reinjected water, as depicted in Figure 4.14. Hot and strong water influx helps to stem decline of reservoir temperature and heat content.

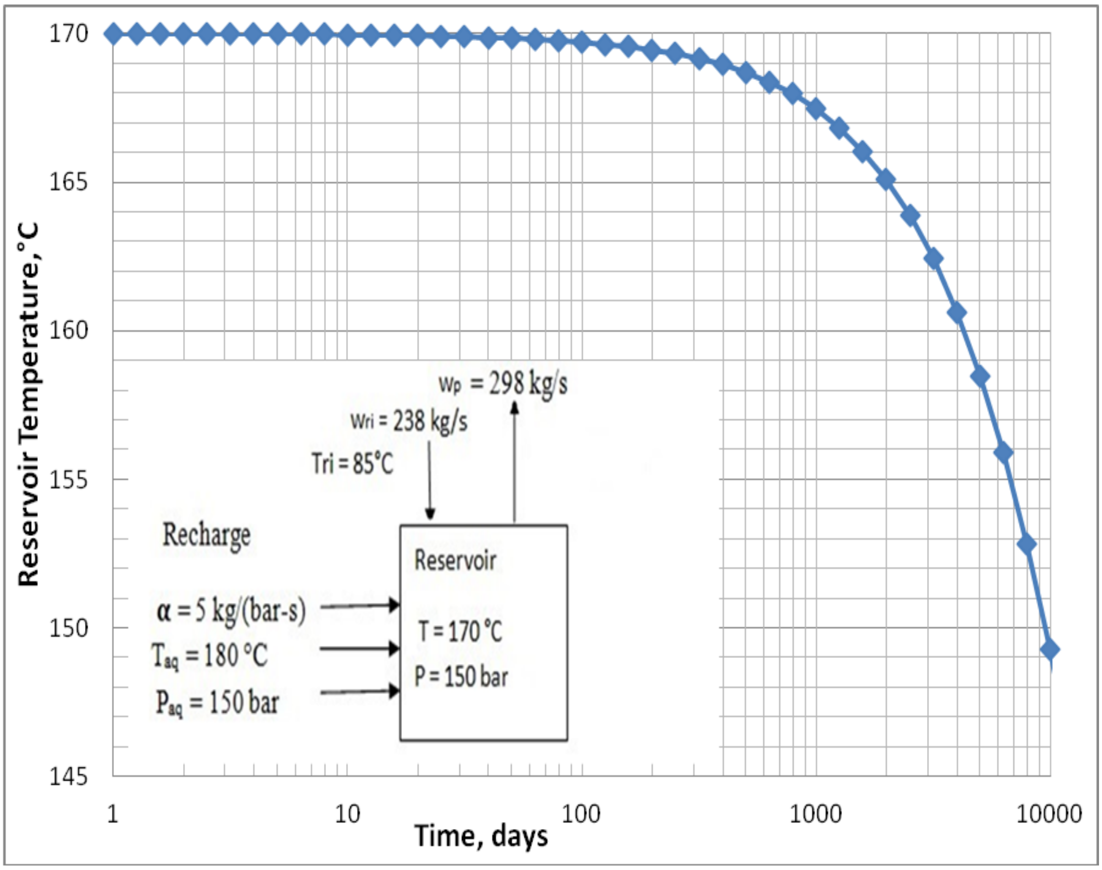

Figure 4.14 : Behaviour of reservoir temperature vs time; cooperative case with unitized two leases.

By end of project life the average reservoir temperature is calculated from Equation 4.3 as $\overline{T}_{res}$ =149 °C.

Since the analytical expression was derived using a single tank model, there is an excellent agreement between values obtained from the analytical expression and the simulator as depicted in Table 4.7 and Figure 4.15.

Table 4.7 : Comparison of average reservoir temperatures obtained from simulator and analytical calculations in Case 2.

	Simulator	Analytical
Time, days	Average Reservoir Temperature, °C	Average Reservoir Temperature, °C
0	170	170
1000	167.5	167
2000	165	165
3000	163	163
4000	161	160
5000	159	158
6000	157	156
7000	155	154
8000	153	152
9000	151	150
10000	149.3	149

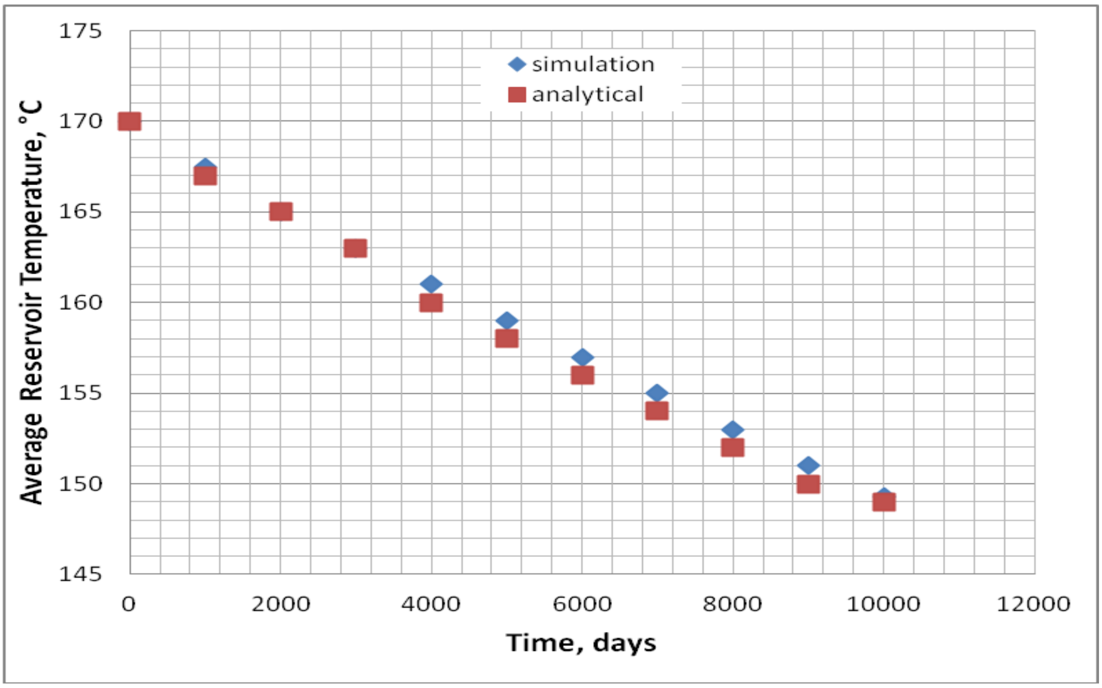

Figure 4.15 : Comparison of simulator and analytical reservoir temperature values; cooperative case with unitized two leases.

The net heat production after 10,000 days is determined analytically from Equation 4.4 to be $1.64 \times 10^{17}\ J$.

Similarly as in Case 1, the simulator is run at time intervals of 1000 days to monitor pressure and temperature drops in order to adjust production rates to yield constant heat withdrawal. Resulting changes in production rates and binary plant thermal efficiency are shown in Table 4.8 and Figures 4.16 and 4.17.

Table 4.8 : Results of varying production rates and thermal efficiencies estimated for cooperative approach with unitized two leases.

Time (days)	w_p (kg/s)	w_{ri} (kg/s)	Thermal Efficiency of binary plant (%)	Change in Thermal Efficiency $(\Delta\eta_{th})$
1000	298	238	12.4	0.2
2000	302	242	12.2	0.4
3000	307	246	12.	0.6
4000	311	249	11.7	0.9
5000	316	253	11.5	1.1
6000	320	256	11.3	1.3
7000	325	260	11.1	1.5
8000	329	263	10.9	1.7
9000	334	267	10.7	1.9
10000	338	270	10.5	2.1

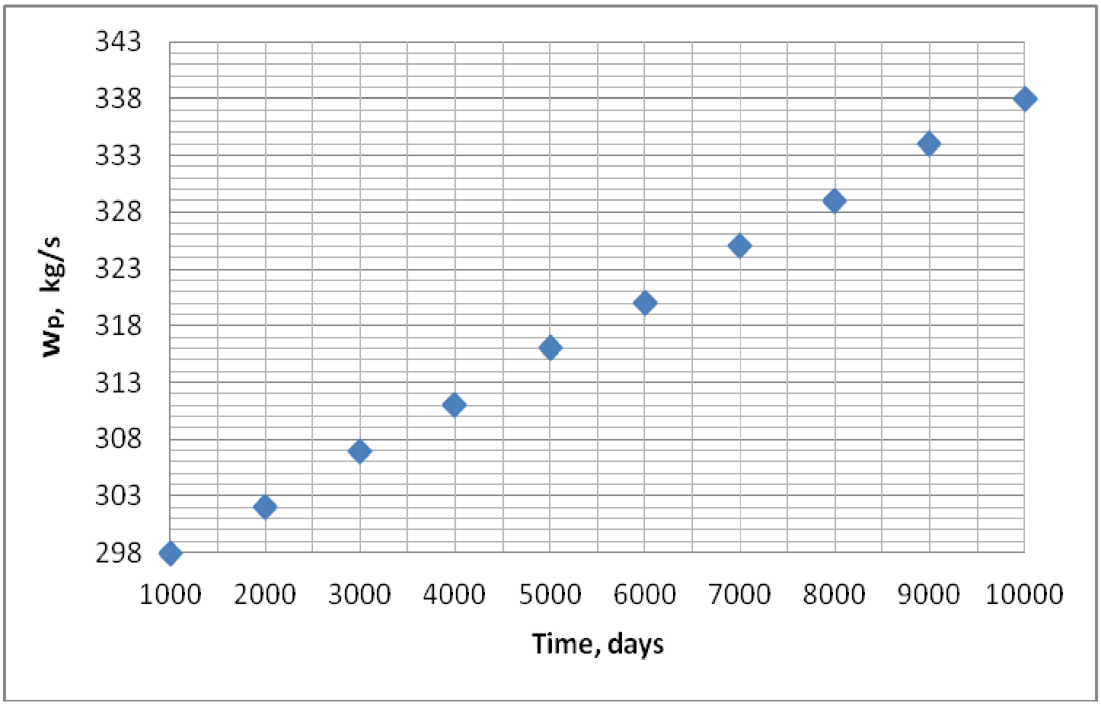

Figure 4.16 : Variation in production rate with time; cooperative case with unitized two leases.

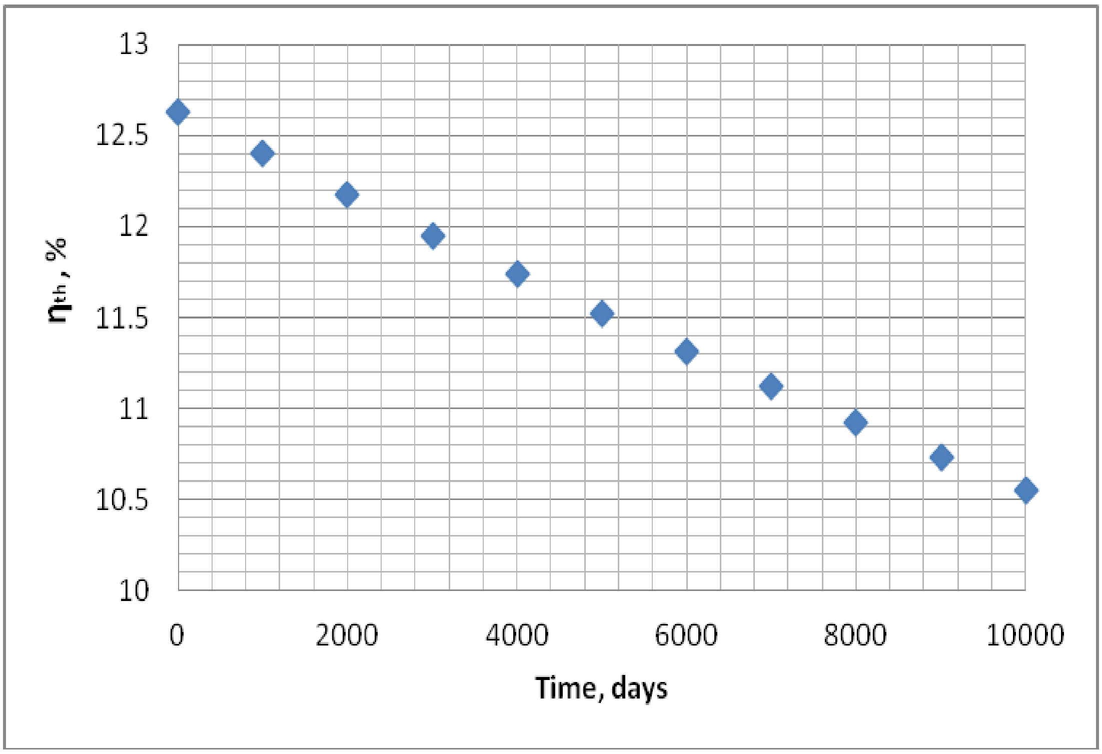

Figure 4.17 : Change in thermal efficiency versus time; cooperative case with unitized two leases.

Production rates increase with time as reservoir temperature falls. Example calculation after 9000 days is shown;

$$298\,kg/s \times 170\,°C = w_p(9000\,days) \times 149.7\,°C$$

$$w_p(9000\,days) = \frac{298\,kg/s \times 170\,°C}{149.7\,°C} = 338\,kg/s$$

At average temperature of the reservoir, T_r being equal to 149.7 °C and inlet geofluid temperature, T_1 as 139.7 °C by 9000 days, thermal efficiency of the binary power plant decreases to; $\eta_{th} = (0.0935 \times 139.7) - 2.3266 = 10.7\ \%$

$$\Delta\eta_{th} = \eta_{th}(0\,day) - \eta_{th}(9000\,days) = 12.6 - 10.7 = 1.9\ \%$$

By end of design life, there is 16.7% reduction in efficiency of the binary power plant in the unitized reservoir.

From Equation 4.4, actual net heat produced for the constant electricity generation is $1.03 \times 10^{17}\,J$.

The comparison of variations in reservoir tempearture and reservoir pressure values from changing production rates is given in Table 4.9 and Figures 4.18 and 4.19.

Table 4.9 : Comparison of average reservoir temperatures and average resevoir pressures for constant and varying production rates.

	Constant w_p and w_{ri}		Varying w_p and w_{ri}	
Time, day	Average Reservoir Temperature, °C	Average Reservoir Pressure, bar	Reservoir Temperature, °C	Reservoir Pressure, bar
0	170	150	170	150
1000	167.5	137.2	167.5	137.2
2000	165	137.2	165.1	137.2
3000	163	137.2	162.7	136.8
4000	161	137.3	160.4	136.9
5000	159	137.3	158.1	136.7
6000	157	137.4	155.9	136.5
7000	155	137.4	153.8	136.3
8000	153	137.4	151.7	136.4
9000	151	137.5	149.7	136
10000	149.3	137.5	147.8	136

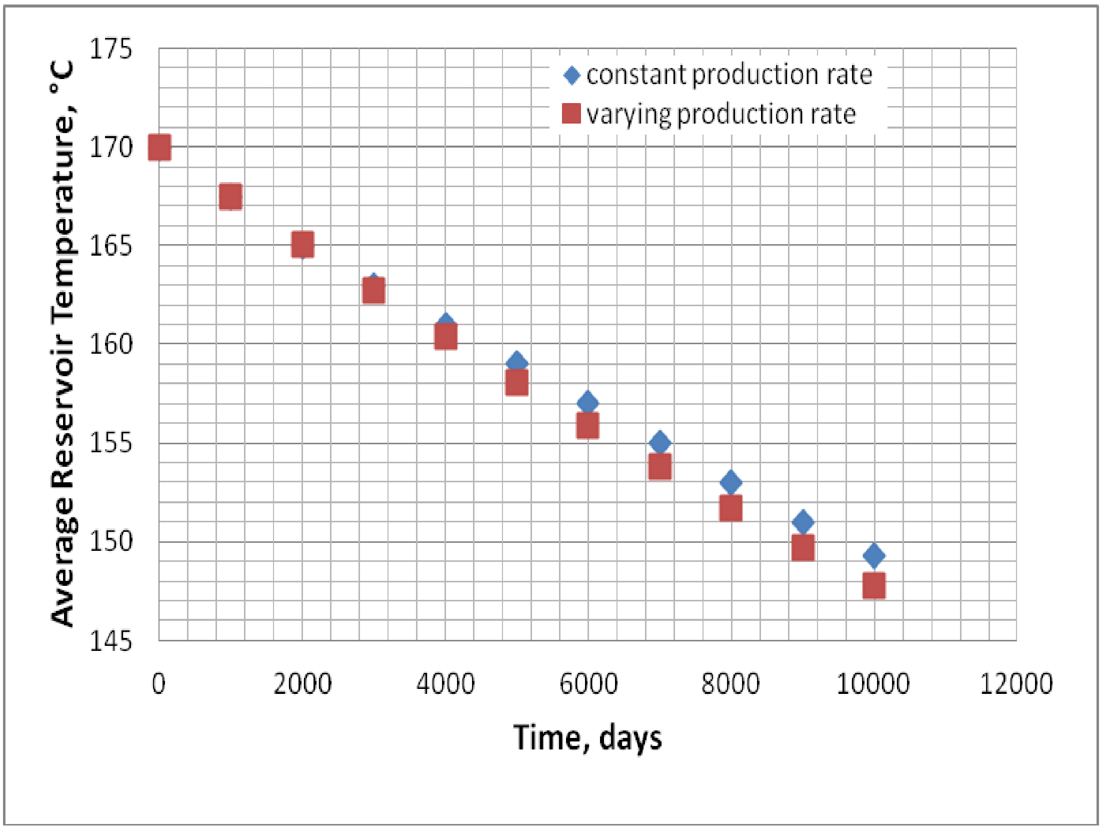

Figure 4.18 : Comparison of reservoir temperatures for constant and varying production rates; cooperative case with unitized two leases.

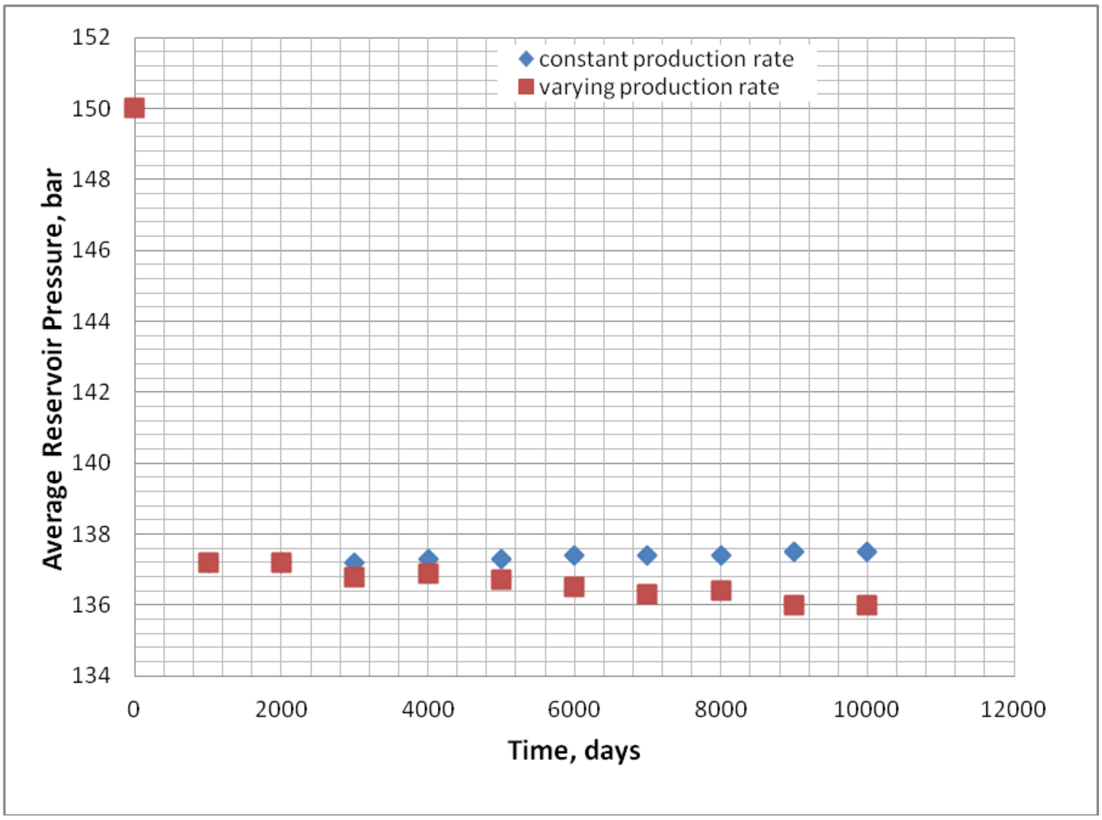

Figure 4.19 : Comparison of reservoir pressures for constant and varying production rates; cooperative case with unitized two leases.

4.5. Case 3: Cooperative Approach with unitized two leases (production in one lease and reinjection in other lease)

Figure 4.20 shows an illustration of unitized case where production is effected in Lease 1 with reinjection in the Lease 2.

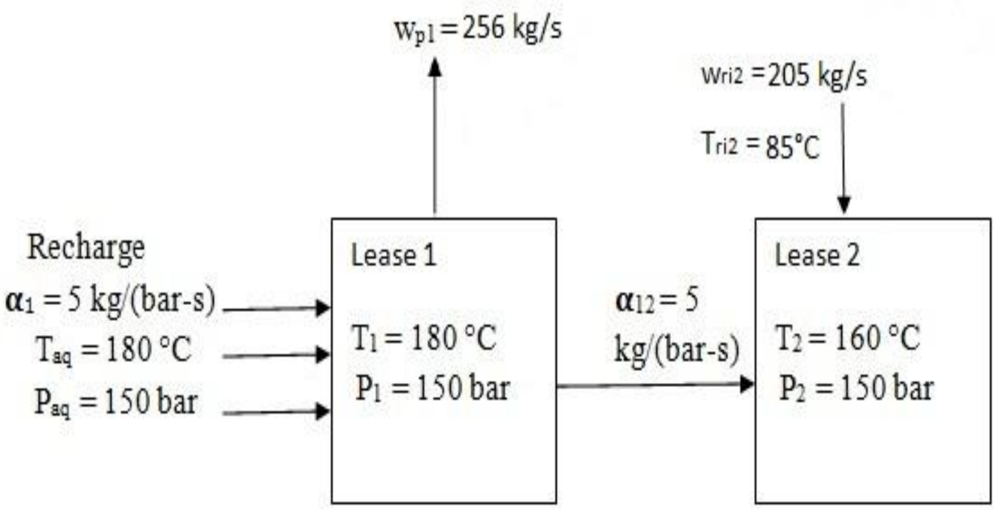

Figure 4.20 : Illustration of cooperative approach with two unitized leases; production in Lease 1, reinjection in Lease 2.

Determining thermal efficiency, production and reinjection rates for reservoir temperature of 180 °C : At a geofluid temperature flowing through the heat exchanger, T_1 being equal to 170 °C, exiting working fluid temperature, T_2 equal to 35°C, specific power output is read from Figure 4.4 as 78 [kW/(kg/s)].

$$\eta_{th} = (0.0935 \times 170) - 2.3266 = 13.6\% = 0.136$$

$$Q_{in} = \frac{Q_{out}}{\eta_{th}} = \frac{10{,}000\, kJ/s}{0.136} = 73{,}529\ kJ/s$$

$$w = \frac{1}{S.P.O} \times Q_{out} = \frac{1}{78[kJ/s/(kg/s)]} \times 10{,}000\, kJ/s = 128\, kg/s$$

For the two power plants(20 MW_e); $w = 128\, kg/s \times 2 = 256\, kg/s$

Reinjection; $w_{ri} = 256\, kg/s \times 0.8 = 205\, kg/s$

Simulation results are shown in Figures 4.21 and 4.22.

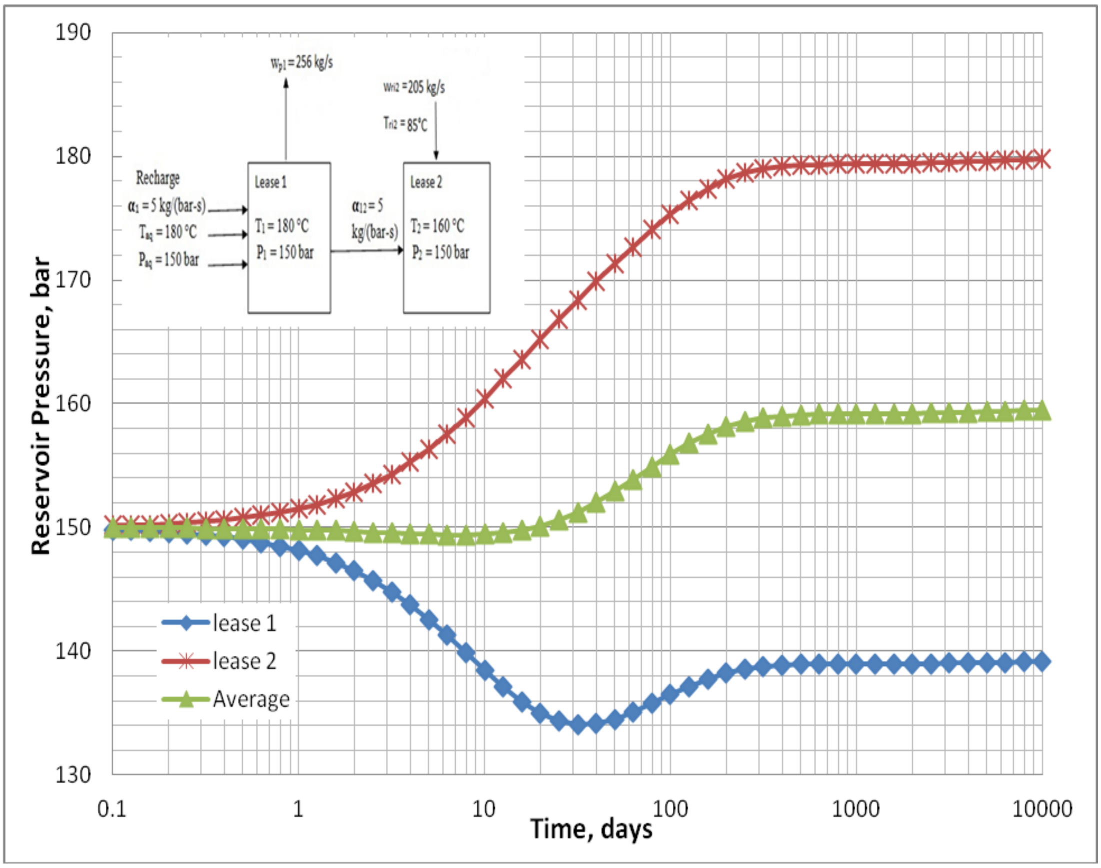

Figure 4.21 : Behaviour of reservoir pressure vs time; cooperative approach with production in Lease 1, reinjection in Lease 2.

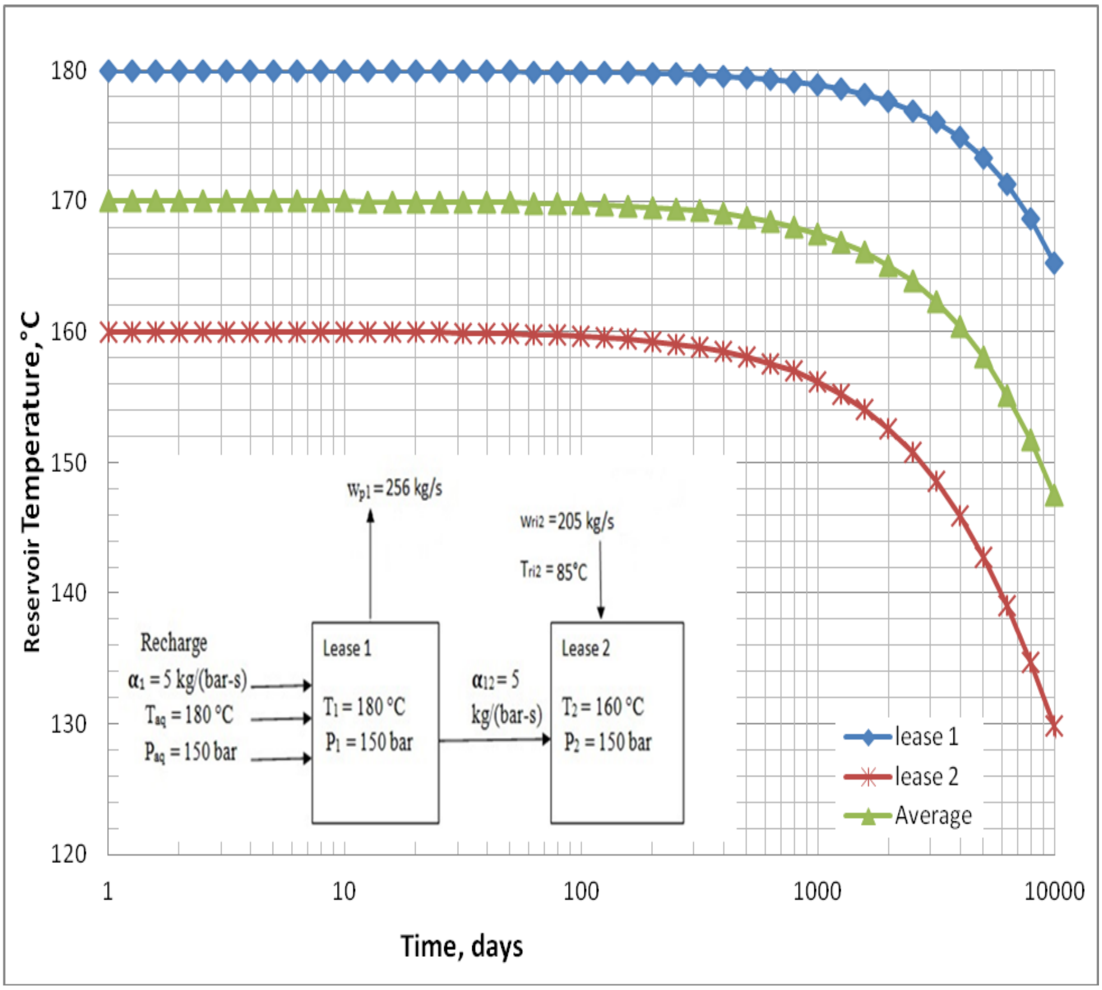

Figure 4.22 : Behaviour of reservoir temperature vs time; cooperative approach with production in Lease 1, reinjection in Lease 2.

Production in Lease 1 causes pressure drop prompting water influx from recharge source as well as from Lease 2. Part of the reinjected water in Lease 2 flows into Lease 1, and so the surplus goes to incease reservoir pressure in Lease 1. Pressure then stabilizes as water influx from the recharge and Lease 2 balances rate of production in Lease 1. Since there is no geofluid production from Lease 2 which as well receives all the reinjected water, pressure in Lease 2 increases to 179.8 bar after 10,000 days.

In Lease 1, pressure declines sharply in the transient stage owing from high withdrawal rate which is not balanced by recharge and influx from Lease 1. Pressure then increases when replenishment becomes signigficant, and then stabilizes at 139.2 bar. Average reservoir pressure is at 159.5 bar by the end of design life.

Equations 3.5 and 3.6, are used to calculate for steady-state pressure drops of the two leases respectively.

$$\Delta P_{ss1} = \frac{w_{pn.1}}{\alpha_{.1}} = \frac{51}{5} = 10.2\,bar$$

$$P_{ss1} = P_i - \Delta P_{ss1} = 150 - 10.2 = 139.8\,bar$$

$$\Delta P_{ss2} = \Delta P_{ss1} + \frac{w_{pn.2}}{\alpha_{.12}} = 10.2 + \left(\frac{-205}{5}\right) = -30.8\,bar$$

$$P_{ss2} = P_i - \Delta P_{ss2} = 150 - (-30.8) = 180.8\,bar$$

The volumetric average steady-state reservoir pressure loss is given by;

$$\overline{\Delta P_{ss}} = \frac{(V_{p1}\Delta P_{ss1}) + ((V_{p2}\Delta P_{ss2}))}{V_{p1} + V_{p2}} = \frac{[0.5\times10^9 \times 10.2] + [0.5\times10^9 \times (-30.8)]}{1\times10^9} = -10.3\,bar$$

$$\overline{P}_{SS} = P_i - \overline{\Delta P} = 150 - (-10.3) = 160.3\,bar$$

Figure 4.22 describes temperature profile of Case 3. Reinjection in Lease 2 causes a decline in temperature. And since it is at a higher pressure, it does not receive hot liquid influx from Lease 1. Temperature in Lease 2 falls to 129.9°C after 10,000 days.

Hot recharge into Lease 1 which is also at the same temperature of 180°C aids in temperature maintenance in Lease 1. Again part of reinjected water which invades Lease 1 from Lease 2, in response to pressure drop, gets heated up before influx and so drop in temperature profile of Lease 1 is minimal . Temperature in Lease 1 drops to 165.2°C by end of design life.

The analytical expression, Equation 4.3, is used to compute for average reservoir temperature by end of 10,000 days to give $\overline{T}_{\text{res}}$ = 151 °C.

The net heat production after 10,000 days is determined analytically from Equation 4.4 as $1.40\times10^{17}\,J$.

Differences in average reservoir temperature values arise between the simulator and analytical average temperature values because the lumped parameter approach was derived for a single tank model. This is shown in Table 4.10 and Figure 4.23.

Table 4.10 : Comparsion of average reservoir temperatures obtained from simulator and analytical calculations in Case 3.

	Simulator	Analytical
Time, days	Average Reservoir Temperature, °C	Average Reservoir Temperature, °C
0	170	170
1000	167.5	168
2000	165.1	166
3000	162	164
4000	160	162
5000	155	160
6000	156	158
7000	154	156
8000	152	154
9000	150	153
10000	147.6	151

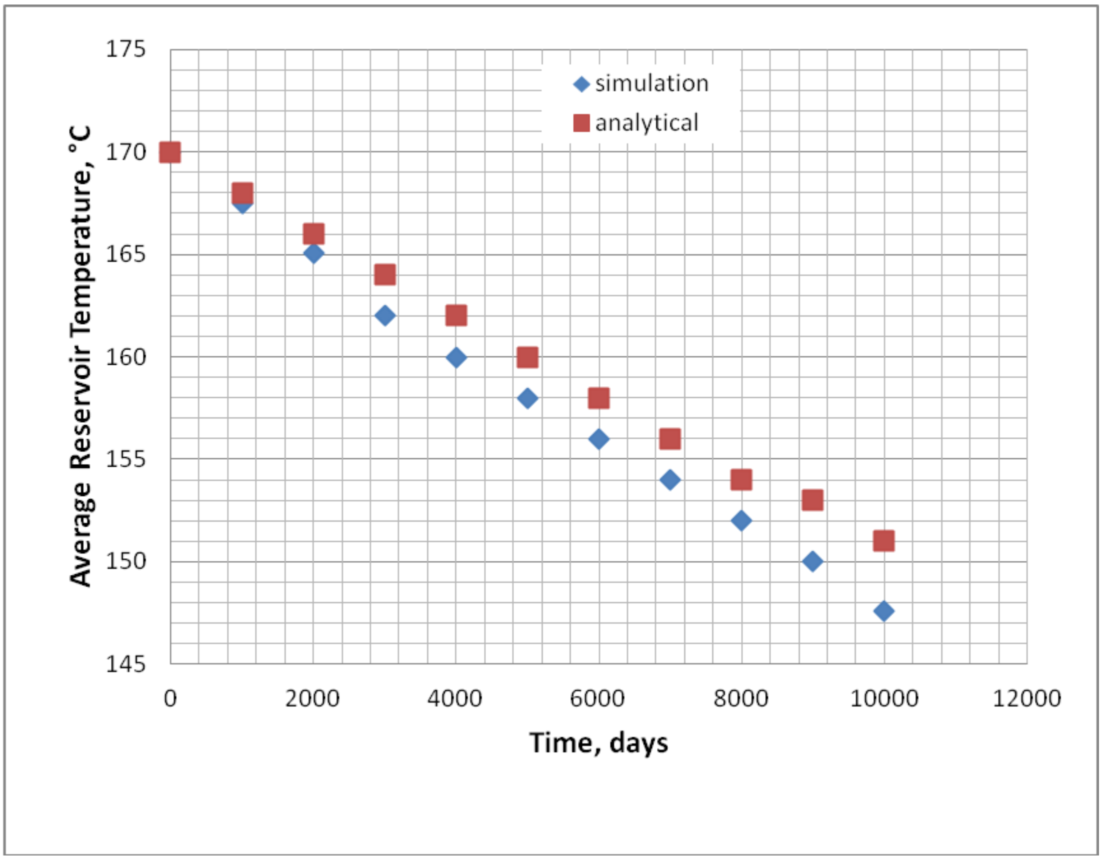

Figure 4.23 : Comparison of simulator and analytical average reservoir temperature values; cooperative approach with production in Lease 1, reinjection in Lease 2.

As with the previous cases, the simulator is run at time intervals of 1000 days to monitor pressure and temperature drops in order to adjust production rates. Subsequent effects on reservoir performance parameters are demonstrated in Table 4.11 and Figures 4.24 and 4.25.

Table 4.11 : Results of varying production rates and thermal efficiencies for cooperative approach with 2 leases, w_p in Lease 1, w_{ri} in Lease 2.

	Unitized Case, Single Tank			
Time, day	w_p, kg/s	w_{ri}, kg/s	Thermal Efficiency of binary plant, %	Change in Thermal Efficiency, $\Delta\eta_{th}$
1000	256	205	13.5	0.1
2000	258	206	13.3	0.3
3000	259	207	13.2	0.4
4000	261	209	13.1	0.5
5000	264	211	12.9	0.7
6000	266	213	12.8	0.8
7000	268	214	12.6	1
8000	271	217	12.5	1.1
9000	274	219	12.3	1.3
10000	277	222	12.1	1.5

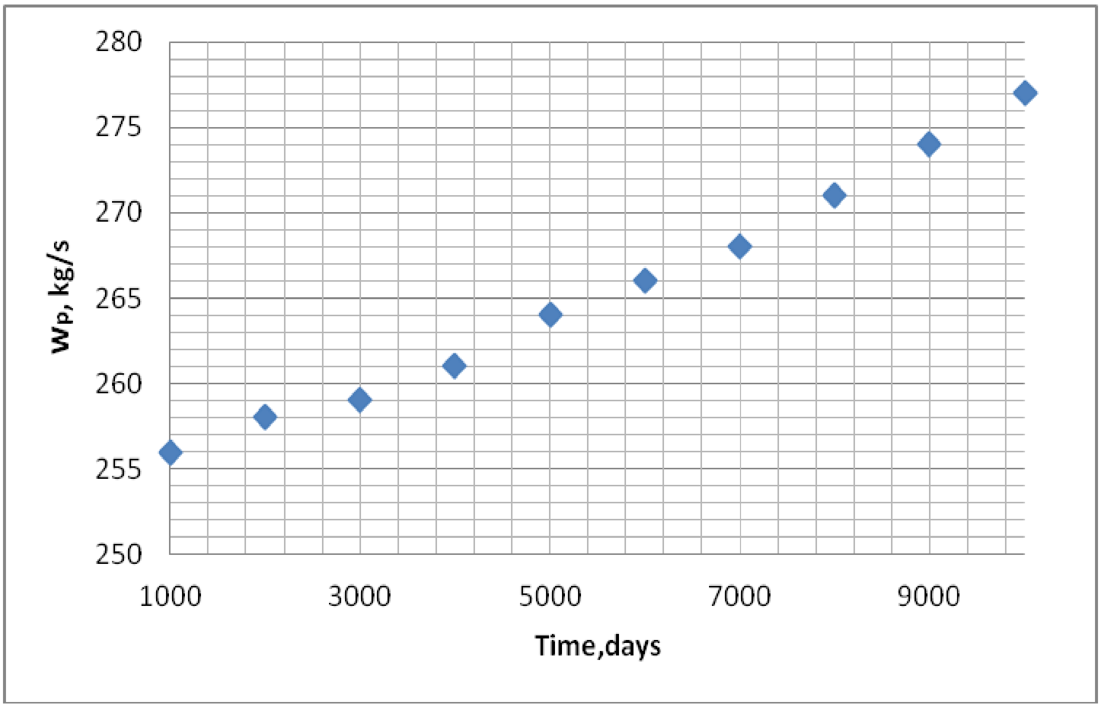

Figure 4.24 : Variation in production rate with time; cooperative approach with production in Lease 1, reinjection in Lease 2.

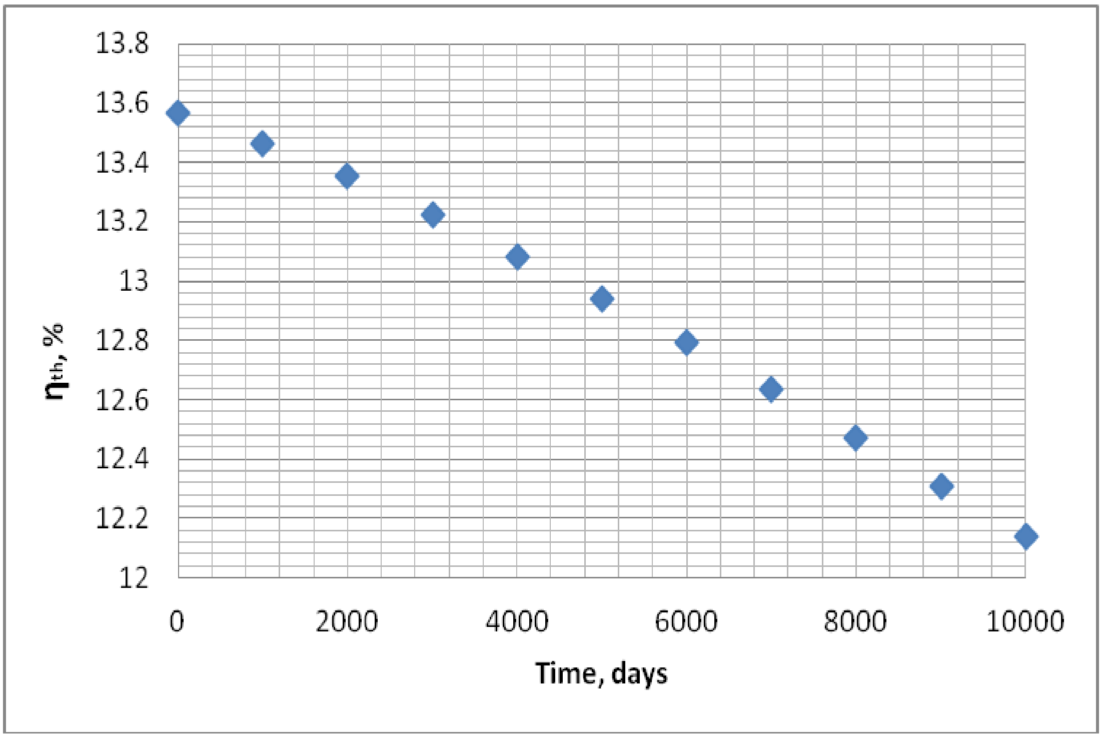

Figure 4.25 : Change in efficiency versus time; cooperative approach with production in Lease 1 and reinjection in Lease 2.

Production rates increase with time as reservoir temperature falls. Example calculation after 5000 days for Lease 1 is shown;

$$256\,kg/s \times 180\,°C = w_p(5000\,days) \times 173.3\,°C$$

$$w_p(5000\,days) = \frac{256\,kg/s \times 180\,°C}{173.3\,°C} = 266\,kg/s$$

At average temperature of the reservoir, T_r being equal to 173.3 °C in Lease 1 and inlet geofluid temperature, T_1 as 163.3 °C by 5000 days, thermal efficiency of the binary power plant decreases to;

$$\eta_{th} = (0.0935 \times 163.3) - 2.3266 = 12.9\ \%$$

$$\Delta\eta_{th} = \eta_{th}(0\,day) - \eta_{th}(9000\,days) = 13.6 - 12.9 = 0.7\ \%$$

Thermal efficiency of the binary power plant in this case has the least decrement, reducing by 11% by end of design life.

Changes in average reservoir temperature and average reservoir pressure values due to increasing production and reinjection rates are compared to values obtained on assumption of constant rates of production and reinjection depicteded in Table 4.12 and Figures 4.26 and 4.27.

Table 4.12 : Comparison of average reservoir temperatures and average reservoir pressures for constant and varying production rates.

	Constant w_p and w_{ri}		Varying w_p and w_{ri}	
Time, day	Average Reservoir Temperature, °C	Average Reservoir Pressure, bar	Average Reservoir Temperature, °C	Average Reservoir Pressure, bar
0	170	150	170	150
1000	167.5	159.2	167.5	159.2
2000	165.1	159.2	165.1	159.1
3000	162	159.3	162.7	159.3
4000	160	159.3	160.2	159.5
5000	158	159.3	157.8	159.5
6000	156	159.4	155.5	159.7
7000	154	159.4	153.2	160
8000	152	159.4	150.9	160
9000	150	159.5	148.7	160
10000	147.6	159.5	146.5	160.1

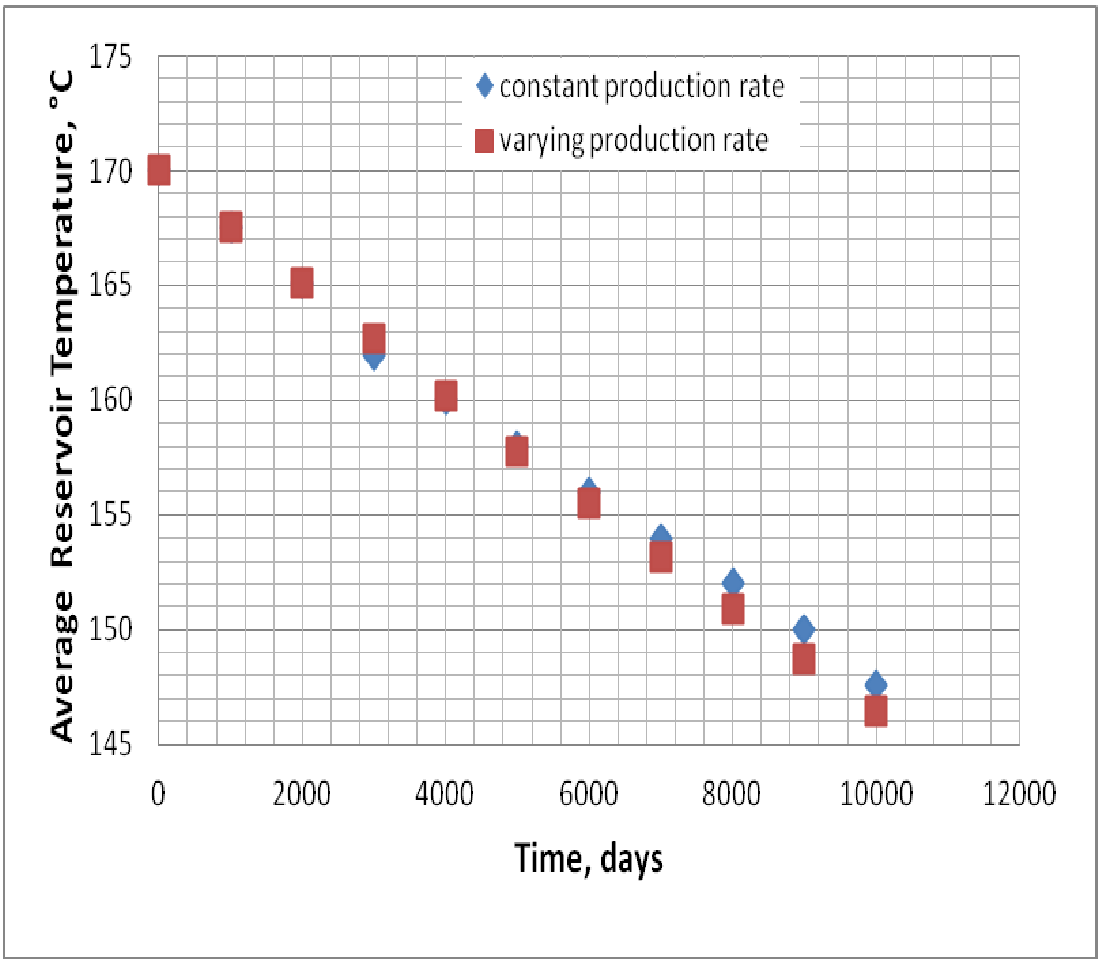

Figure 4.26 : Comparison of average reservoir temperatures for constant and varying production rates; cooperative approach with production in Lease 1 and reinjection in Lease 2.

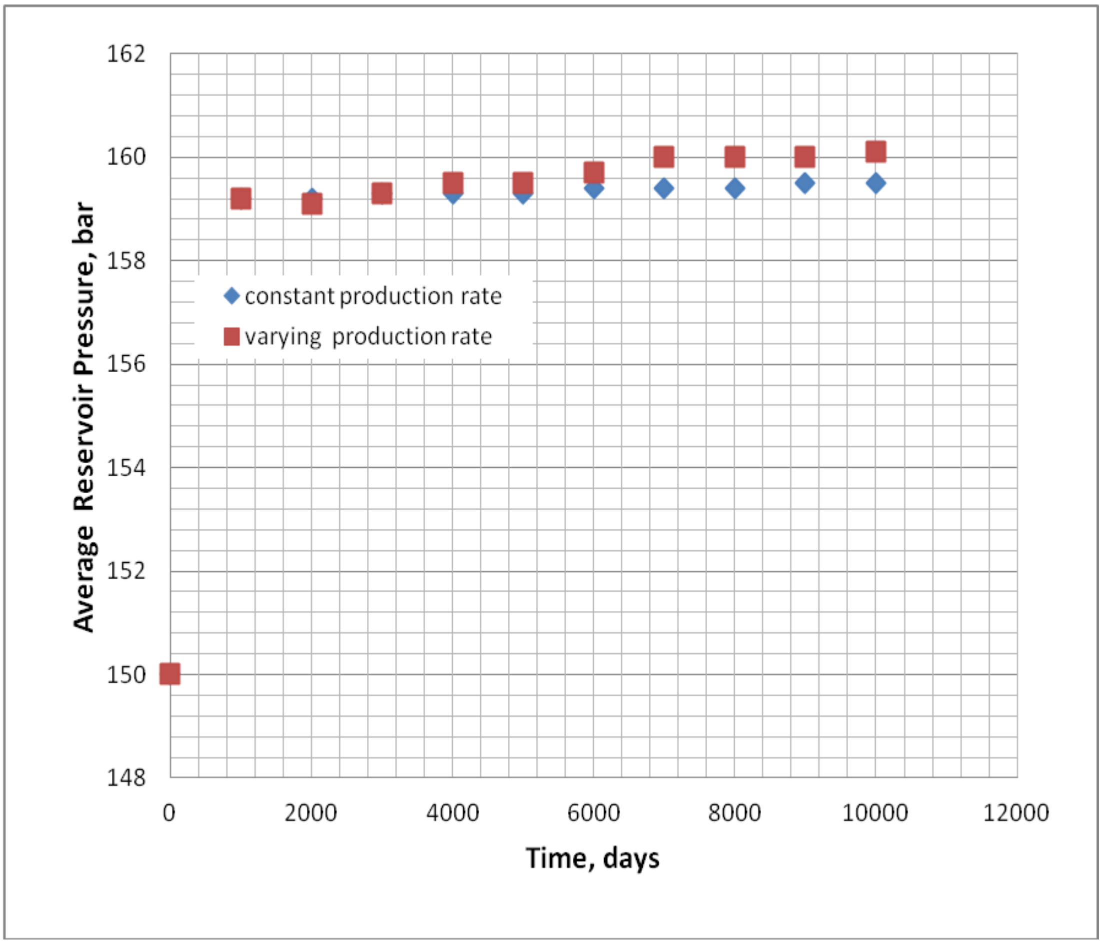

Figure 4.27 : Comparison of average reservoir pressures for constant and varying production rates; cooperative approach with production in Lease 1 and reinjection in Lease 2.

From Equation 4.4, actual net heat produced for the constant electricity generation is $8.54 \times 10^{16} J$.

4.6. Discussion of Results

Comparative analysis among the 3 cases is conducted to determine the most favorable scenario to carry out the proposed consistent 20 MW_e power generation project, based on changing production rates. Reservoir performance parameters chosen for this selection are average reservoir pressure, average reservoir temperature, net heat produced, and binary power plant thermal efficiency.

Figures 4.28, 4.29 and 4.30, describe changes in the reservoir performance parameters.

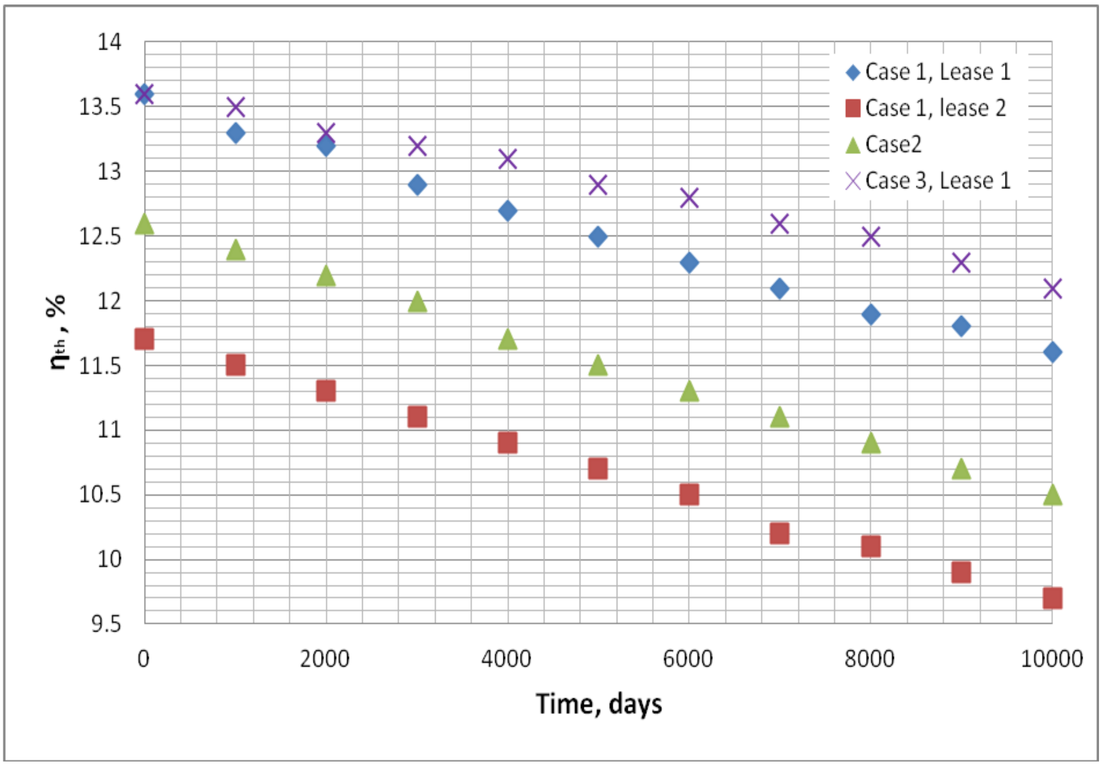

Figure 4.28 : Comparison of binary power plant thermal efficiencies among all cases.

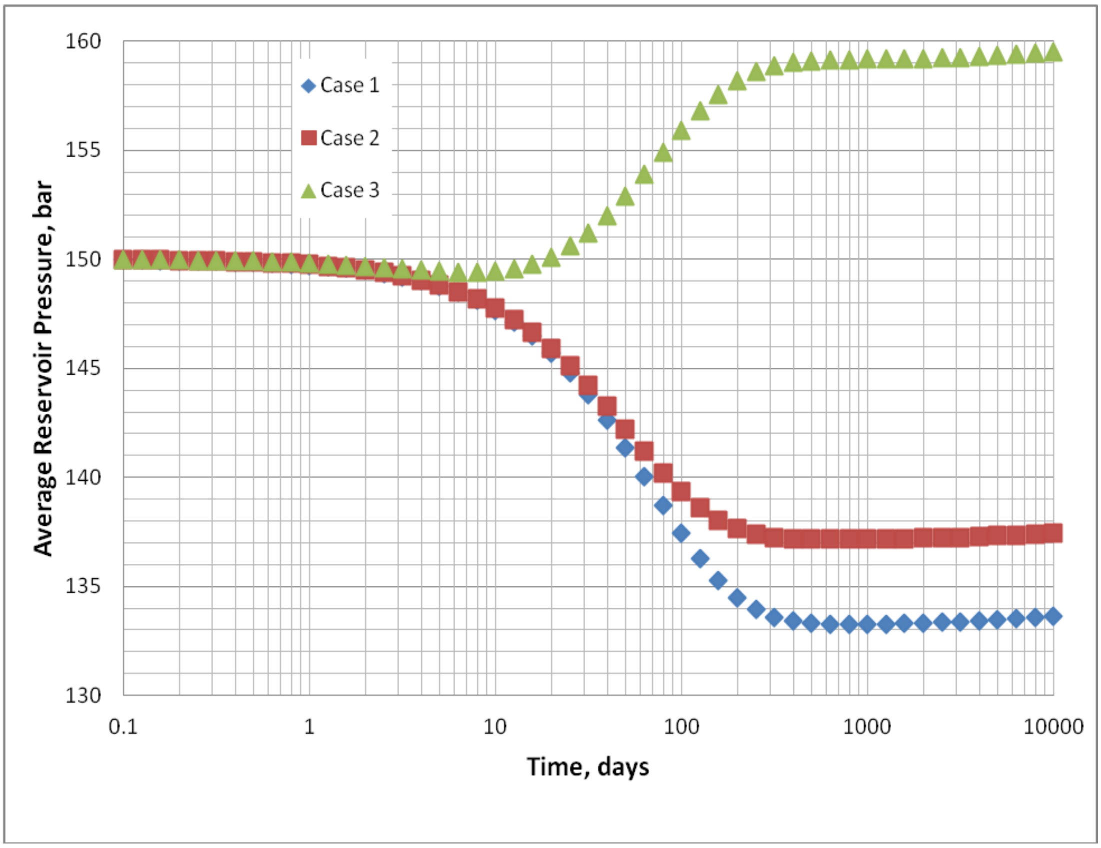

Figure 4.29 : Comparison of average reservoir pressures among all cases.

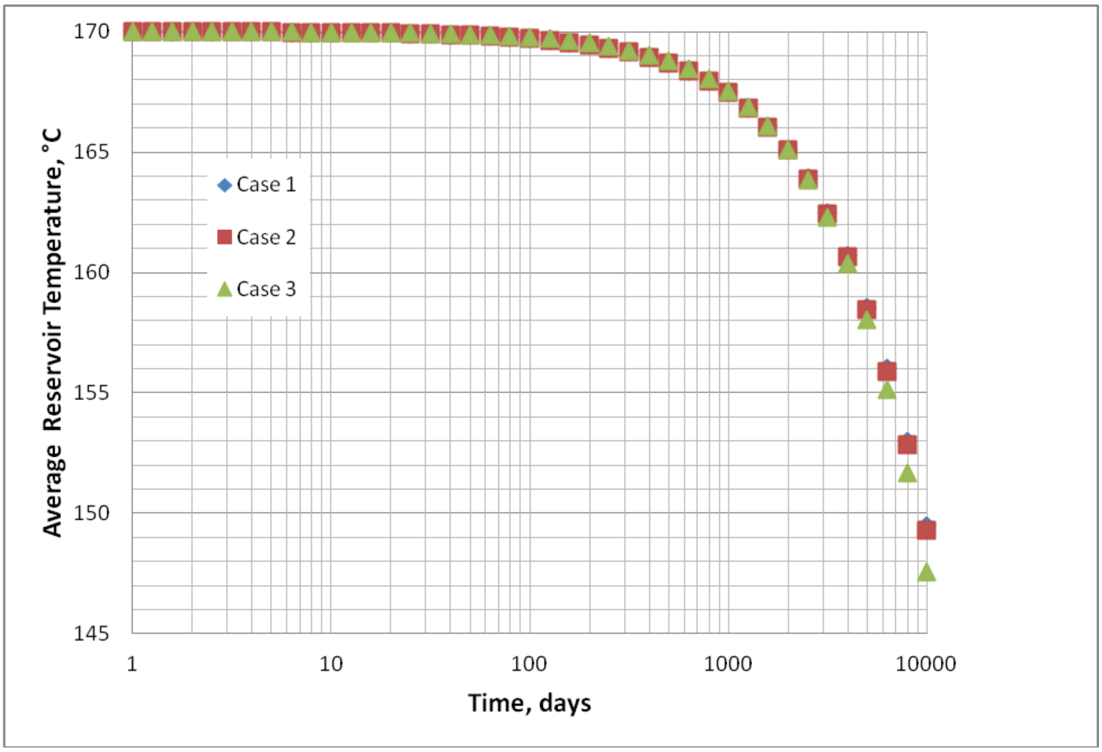

Figure 4.30 : Comparison of average reservoir temperatures among all cases.

Compilation of the average reservoir pressure, average reservoir temperature, net heat produced, and thermal efficiency of the binary power plant, of the 3 cases by the end of the design life is provided in Table 4.13.

Table 4.13 : Comparison of results between cases at end of 10,000 days.

CASE	P_{avg}, bar	T_{avg}, °C	Net Heat Produced, J	Thermal Efficiency, η_{th}, %	
				Lease 1	Lease 2
Case 1 : Competitive approach with two leases	131.7	148.6	1.06×10^{17}	11.6	9.7
Case 2 : Cooperative approach with unitized two leases	136	147.8	1.03×10^{17}	10.5	
Case 3 : Cooperative approach with unitized two leases (production in one lease and reinjection in other lease)	160.1	146.5	8.54×10^{16}	12.1	

The competitive approach though records the highest value in average reservoir temperature and net heat produced, registers the lowest average reservoir pressure and develops the highest decline in initial binary power plant thermal efficiencies.

Unitized approach where system is treated as a single tank registers is second best in all the performance parameters.

Unitized approach where production is operationalised in Lease 1, with reinjection in Lease 2 gives the highest average pressure. Reservoir pressure is a vital tool for measuring sustainability of a reservoir and by this criterion, Case 3 is most favorable. Case 3 records the least net heat produced, at $8.54\times10^{16}\,J$, which is still desirable compared to the other two cases. Again it has the lowest drop from initial binary power plant thermal efficiency, decreasing by 11% at end of design life to 12.1%. Comparatively, the average reservoir temperature after 10,000 days at 146.5 °C is very close to that of Case 1, which records the highest at 148.6°C, a minor difference of 2.1 °C. It therefore represents the most desirable development scenario among all the examined cases, for constant 20 MW_e electricity generation capacity.

5. CONCLUSIONS AND RECOMMENDATIONS

Geothermal reservoir is indivisible by nature and so unregulated development of tracts overlying a straddled reservoir results in physical waste and under-utilization of resource, characterised by high rate of pressure decline and reduced total heat recovery, high economic waste, as well as environmental degradation.

The solution proposed to resolve this problem is unitization. It facilitates for high productivity, sustainability, and profitability of the geothermal reservoir.

Three hypothetical scenarios of the one-tank and two-tank models regarding differences in reservoir temperature, have been analysed to study reservoir pressure and reservoir temperature behaviour relative to reservoir fluid production and time, with reinjection, under competitive and cooperative managements for constant electricity generation capacity. The significance of this thesis is emphasized on selection of the most suitable development approach to execute this project for a straddled reservoir shared by two different lease holders As such, all the cases are evaluated in terms of average reservoir pressure, average reservoir temperature, net heat produced, and thermal efficiency of the binary power plant.

Out of the 3 cases investigated, unitized approach where production is in Lease 1 with reinjection in Lease 2, is the most desired mode of operation to feed the 20 MW_e capacity binary power plant for the purpose of electricity generation. This case works best, because of well coordinated and informed technical decisions on appropriate well planning based on extensive integrated data. Hot fluid zones are identified for production and are well separated from cooler regions, in which reinjection wells are to be located. The purpose of proper location of wells is to achieve the most efficient and sustainable energy production. As the reservoir section under Lease 1 is directly connected to the recharge source, from which the reinjection well is located far away in Lease 2, replenishment of produced fluids is at an adequate rate ensuring high average reservoir pressure. Locating the reinjection wells at a safe distance from the production wells in Lease 2, the temperature of the hot water zone is kept under control. Thus, the net heat produced would be very favourable, since the reinjected fluid is channelled through the reservoir section under Lease 2 to ensure minimal drop in temperature of the reservoir section under Lease 1, which enjoys hot liquid influx from the infinite size recharge source (aquifer). Case 3 also experiences the least drop in thermal efficiency of the binary power plant by the end of the design life.

It can be concluded that the owners of straddled leases should be encouraged or imposed on to act in a cooperative strategy for an unitized management of land, geothermal energy, any heat or energy source surrounding the geothermal waters, and ecosystem to derive maximum benefits for all stakeholders and safeguard public interests.

REFERENCES

ASME (2006). Steam Tables Compact Edition, ASME, New York, USA.

Asmus, D., and Weaver, J. (2006). Unitizing Oil and Gas Fields Around the World: A Comparative Analysis of National Laws and Private Contracts. University of Houston; Public law and legal theory series, A-05.

Axelsson, G., and Gunlaugsson, E. (2000). Long-term Monitoring of High- and Low-enthalpy Fields under Exploitation. Proccedings of World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan, May.

Bertani, R. (2015). Geothermal Power Generation in the World: 2010-2014 Update Report. Proceedings of the World Geothermal Congress 2015 , Melbourne, Australia, 19-25 April.

Bodvarsson, G.S., Pruess, K., and Lippmann, M.J. (1986). Modelling of Geothermal systems. Journal of Petroleum Technology 38, 1007-1021.

Cargill, K., Conover, R.D. (1978). Concepts in Unitization of Federal Geothermal Leases. Geothermal Resources Council, Volume 2, 67-70, July.

DiPippo, R. (2004). Second Law Assessment of Binary Plants for Power Generation from Low-Temperature Geothermal Fluids. Geothermics 2004; 33:565-586.

DiPippo, R. (2005). Geothermal Power Plants: Principles, Applications and Case Studies. Elsevier Advanced Technology, Oxford, England.

Environmental Management Associates, Inc. (2004). Geothermal Power Company, LLC, Geysers Geothermal Exploration Project, Initial Study. California, USA.

Geothermal Energy Association Issue Brief: Additional Economic Values of Geothermal Power. (2015). February.

Grant, M. (2013). Geothermal Reservoir Engineering. Oxford, Elsevier Science.

International Energy Agency. (2014). Key World Energy Statistics, Paris, France.

Jennejohn, D. (2010). Green Jobs Through Geothermal Energy. Geothermal Energy Association, October.

Ketilsson, J., Petursdottir, H.T., Thoroddsen, S., Oddsdottir, A.L., Bragodottir, E.R., Gudmundsdottir, M., and Johannesson, G.A. (2015). Legal Framework and Natural Policy for Geothermal Development in Iceland. Proceedings of World Geothermal Congress 2015, Melbourne, Australia, 19-25 April.

Korkmaz, E.D., Serpen, U., and Satman, A. (2014). Geothermal boom in Turkey: Growth in identified capacities and potentials. Geothermics 2014; 68:314-325.

Lueck, D., and Schenewerk, P. (1996). An Economic Analysis of Unitized and Non-unitized Production. SPE 36577.

Liu, J., Chen, X., and Guo, W. (2013). Volcanic Natural Resources and Volcanic Landscape Protection: An Overview. Intech 2013.

Lund, J. (2011). Development of Direct-Use Projects. Proceedings of the 36^{th} Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA, January 31 – February 2.

MIT Report. (2006). The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21^{st} Century.

Moon, H., and Zarrouk S.J. (2012). Efficiency of Geothermal Power Plants: A Worldwide Review. Procedings of New Zealand Geothermal Workshop 2012, Auckland, New Zealand, 19-21 November.

Muffler, L.P.J. (1979). Assessment of Geothermal Resources of the United States: U.S. Geological Survey, Circular 790.

Oliver, E., and Umpleby, J.B. (1930). Principles of Unit Operation. AIME, New York Meeting, February.

Onur, M., Sarak, H., Tureyen, O.I, and Satman, A. (2008). A New Non-Isothermal Lumped-Parameter Model for Low-Temperature Liquid-Dominated Geothermal Reservoirs and Its Applications. Proceedings of the 33rd Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA, 28-30 January.

REN21. (2015). Renewables 2015, Global Status Report, Paris, France.

Robinson, J. (1975). Environmental Constraints on Geothermal Development. SPE 5384.

Rodriguez, E., Harvey, S.H., Asbjornsson. (2014). Review of H_2S Abatement Methods in Geothermal Plants. Proceedings of the 38th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA, 24-26 February.

Russel, J.E., Hoglund, F.E., and Dutton, G. (1972). Statutory Unitization: The Engineering Aspects of An Energy Recovery Measure. SPE 3965.

Sagun, M.P. (1992). Binary Power Generation from Waste Heat: A Feasible Improvement to Operating Geothermal Power Plants. UNU Geothermal Training Programme, NEA, Iceland. Report 12.

Sanyal, S.K. (2005). Sustainability and Renewability of Geothermal Power Capacity. Proceedings of World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.

Sarak, H., Onur, M., and Satman A. (2005). Lumped–Parameter Models for Low-Temperature Geothermal Fields and Their Application. Geothermics 2005; 34:728-755.

Satman, A. (2010). Sustainability of a Geothermal Reservoir. Proceedings of World Geothermal Congress, Bali, Indonesia, 25-29 April.

Satman, A., Sarak H., Onur, M., and Korkmaz, E.D. (2005). Modelling of Production/Reinjection Behaviour of the Kizildere Geothermal Field by A Two-Layer Geothermal Reservoir Lumped-Parameter Model. Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.

Tureyen, O.I., and Akyapi E. (2011). A Generalised Non-Isothermal Tank Model for Liquid Dominated Geothermal Reservoirs. Geothermics 40 (2011), 50-57.

Tureyen, O.I., and Satman, A. (2013). Multiple License Holders in The Same Area: An Expected Risk to Geothermal Development in Turkey. Proceedings of the 38th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA, 11-13 February.

Tureyen, O.I., Sarak, H., Altun, G., and Satman, A. (2015). A Modeling Analysis of Unitized Production: Understanding Sustainable Managementt of Single-Phase Geothermal Resources with Multiple Lease Owners. Geothermics 55 (2015), 159-170.

Url-1 <*http://*www.law.cornell.edu/cfr/text/43/3280.2. >, date retrieved 30.08.2015.

Williams, C.F., Reed, M.J., and Mariner, R.H. (2008). A Review of Methods Applied by the USGS in the Assessment of Identified Geothermal Resources, USGS Open-File Report, 2008, 1296,

(http://pubs.usgs.gov/of/2008/1296/).

Williams, C.F.. Reed, M.J., and Anderson, A.F. (2011). Updating the Classification of Geothermal Resources. Proceedings of the 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California, January 31 – February 2.

World Energy Council (2013). World Energy Resources, 2013 Survey. London, United Kingdom.

CURRICULUM VITAE

Name Surname: Suleman SALIA

Place and Date of Birth: Kumasi (Ghana), 6th January 1985

E-Mail: massahsulemanahoo.com

B.Sc.: Civil Engineering

PROFESSIONAL EXPERIENCE AND REWARDS:

I was the captain of SPE-ITU Petrobowl team at SPE Annual Technical Conference and Exhibition in Amsterdam (October 2014).